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SEPTEMBER 1933

MECHANICS OF FORMATION OF SALT DOMES WITH SPECIAL REFERENCE TO GULF COAST SALT DOMES OF TEXAS AND LOUISIANA[1]

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ABSTRACT

The salt of the salt domes of some areas is known to be sedimentary. Geological observation of those domes and laboratory experimentation show that salt flows plastically under differential pressure. The German salt domes are known to have been formed by the plastic flowage of the Zechstein salt series. Any type of differential pressure should tend to produce plastic flowage of sedimentary salt whenever certain critical conditions such as those of pressure, temperature, and time have been exceeded. The plausible sources of pressure are two: (1) the static pressure of the overlying sediments; and (2) the dynamic pressure of tangential compression or thrust. Under (1), growth of the dome by upthrust can take place only if the available energy is sufficient both to overcome friction and to uplift the salt core and some sediments against gravity; growth of the dome by downbuilding can take place if the mother salt bed is sinking in earth space; the position of maximum uplift is below that of isostatic equilibrium of the salt core; and the form of the salt dome should evolve progressively through a characteristic series of forms. Under (2), the horizontal dynamic pressure will act indirectly upward through anticlines and downward through synclines in competent beds; and directly through horizontal squeezing of the salt in relatively upthrust cores. The static thrust of (1) will be active and may be more important than the dynamic thrust of (2); the position of maximum upthrust of the salt core may be far above its position of isostatic equilibrium; the form of the domes should be varied.

The Gulf Coast domes have been formed by the plastic flowage of sedimentary salt intrusively into the overlying sediments. The evidence for that origin of the domes comes from the structure which is revealed by oil-field drilling, from algal remains in the salt, and from the close similarity of the American salt domes to the German salt domes. The age of the salt is greater than most of the Lower Cretaceous. The motive force of the formation of the domes has been the static weight of the sediments. Growth of the domes has taken place throughout the Tertiary and has taken place on a few domes in the most recent past. There was no dynamic tangential compression in the Gulf Coastal Plain area during the Tertiary and Quaternary; therefore, the motive

[1] Read in preliminary form before the Association at the San Antonio meeting, March 19, 1931. Rewritten manuscript received, May 30, 1933.

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force presumably must have been the static thrust of the sediments. Subsidence of the mother salt bed took place almost continuously through the Tertiary and into the Quaternary. The difference between the specific gravity of the salt and of the sediments is small; and the calculated force of upthrust is small, rather too small to overcome friction and to uplift the salt core and some sediments against gravity. Growth of the domes, therefore, must have been largely by downbuilding. Partially corroboratory evidence is given by the concomitant cessation of growth of the Clay Creek dome and cessation of the regional subsidence of the general surrounding area. But some actual upthrust has taken place on the Gulf Coast domes; and, as theoretically expectable, it tends to be greater on the domes of larger diameter. Growth has not continued into recent time on all the domes and has ceased finally at different times on different domes. The law holds crudely that the deeper the dome, the older the time of cessation of growth. The final cessation of growth in general may have been caused by exhaustion of the salt in the mother salt bed, attainment of isostatic equilibrium, frictional freezing of the salt core to the sediments, and, in the case of downbuilding, by cessation of the subsidence. The succession of retrograde movement of the salt core after the cessation of growth is suggested, inconclusively, by the Clay Creek dome. The presence of rim synclines has been suggested by the results of torsion-balance surveys, but has not been identified from geologic data. Rim synclines could be formed: (1) by solution of the flank of the salt, and (2) by the pushing-in of the deep flank of a flaring salt core in the growth of the dome. Overhang of the salt and cap is present in two types: (1) tilting of the vertical axis of the dome, and (2) mushrooming (Barbers Hill). Type (1) is produced perhaps by the seaward flowage of the deeper sediments. The explanations of type (2) are not satisfactory.

PART I

THEORY OF FORMATION OF SALT DOMES

FORMATION BY PLASTIC FLOWAGE OF SEDIMENTARY SALT

The theory of the formation of salt domes by the plastic flowage of sedimentary salt beds under differential pressure is accepted rather generally by salt-dome geologists. The possibility of the flowage of the salt has been shown by Van Tuyl[3] and many others. According to his conclusions, burial of salt to a depth of 12,000 feet should be sufficient to produce upward flowage of the salt into fissures in the overlying strata, if the pressure in the subsurface increases at the rate of one pound per square inch per vertical foot of depth (the rate produced by sediments of a density of 2.3), and if the temperature increases downward at the rate of 1° C. per 100 vertical feet; the lubricating effect of water at the border of the salt cores also may be more important than is generally supposed. Fulda found very much higher pressures necessary for the flowage of salt. Actual flowage of the salt at the surface has been reported from the Persian salt domes. The salt cores of some of the domes form low mountains which rise to a maximum elevation of 800 meters above the surrounding formations. The salt at the base of a few of the larger salt mountains is reported to have flowed down the adjacent valleys and to have formed salt "gla-

[3] F. M. Van Tuyl, "Contribution to Salt Dome Problem," *Bull. American Assoc. Petrol. Geol.*, Vol. 14, No. 8 (August, 1930), pp. 1040–47.

ciers." From the data of the Persian salt domes, Martin Lees estimates that a column of salt 1,100 meters (±50 per cent) high will produce flowage of the salt. The argument for that flowage of the salt at the surface in Persia does not bring conviction to the mind of the writer, but the geology of the known salt domes strongly suggests flowage of the salt at shallower depths than those which the laboratory experiments seem to necessitate. The original and the conclusive evidence of the formation of the salt domes by the plastic flowage of sedimentary salt series comes from the studies of the North German salt domes. The Zechstein salt series of North Germany is a definite stratigraphic series. The structure and composition of the salt domes and ridges is well exposed in the potash mines and test drill holes. The normal character of the salt series is well exposed in potash mines and test holes which lie off the salt domes. The salt cores of the domes and salt ridges can be seen to have been formed by the plastic flowage of the normal Zechstein salt series. The similarity of the Gulf Coast salt domes and of the salt domes elsewhere in the world to the salt domes of North Germany forces the broader conclusion that salt domes generally are produced by the flowage of plastic sedimentary salt series. That conclusion is strengthened for the Gulf Coast salt domes by the occurrence of fossil algae in the sylvite of a core from the Markham salt dome.

MOTIVATING FORCE

The more plausible, conventional theories[4] in regard to the motivating force which produces the plastic flowage of the salt to form salt domes and ridges are two: (1) tangential (horizontal), dynamic compression is the motivating force, according to one theory; and (2) the static downward thrust of the overburden of relatively heavier sediments upon the relatively lighter salt of the mother salt beds is the motivating force according to the other theory. Other theories have been suggested in the past but have been rather generally discredited. Those two main alternative theories should be regarded, however, as incomplete statements of opposing special cases of a more general theory.

Plastic flowage of a sedimentary bed must take place, if some critical point in conditions is exceeded. That critical point should depend on a complex interdependent relation of character of the bed, tem-

[4] For the discussion of the many other theories, see: E. L. DeGolyer, "Origin of North American Salt Domes," *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol., 1926), pp. 1–44; Hans Stille, "Upthrust of Salt Masses of Germany," *ibid.*, pp. 142–63; and E. L. DeGolyer, "Origin of the Salt Domes of the Gulf Coastal Plain of the United States," *Jour. Inst. Petrol. Tech.* (London), Vol. 17, No. 92 (June, 1931), pp. 331–33.

perature, pressure, water content, and time. Differential pressure on a plastic sedimentary bed which is under conditions beyond that critical point, should tend to produce flowage of the plastic sediment, whether the pressure is dynamic tangential thrust or the static thrust of the weight of the overlying sediments.

FORMATION OF DOMES BY STATIC THRUST OF OVERLYING SEDIMENTS

The static thrust of the weight of the overlying sediments should tend to produce upward flowage of any plastic sediment at places at which the downward pressure on, and the resistance to upthrust of, a plastic sedimentary bed is less than normal. That upward flowage should tend to continue until the downward pressure of the upthrust prism of sediments plus the downward pressure upon its crest equals the downward pressure of the normal sediments. The state of equilibrium and isostatic compensation will be attained by slight upthrust of a plastic sediment which is heavier than the normal sediments, but, if the plastic sediment is lighter than the normal sediments, isostatic compensation will be attained only by upthrust of the plastic sediment well above the level of the top of the normal sediments. The starting of the flowage will be dependent on the plasticity of the sediment and the existence of the place of lessened pressure upon, and lessened resistance to the upwelling of, the plastic sediment, but will not depend on the relative density of the plastic sediment compared with the normal sediments. Positive buoyancy of an uplifted prism of a plastic sediment, such as salt, which is lighter than the surrounding sediments, will advance the upthrust of the prism. Negative buoyancy of the uplifted prism, on the other hand, would tend to retard the continuance of the upthrust.

Potential energy which may be used to effect further flowage of the salt will be afforded by an upthrust salt core which has not attained isostatic compensation. To produce actual upthrust of the salt core, that energy must be sufficient (1) to overcome internal friction within the salt; (2) to overcome external friction between the salt and the surrounding sediments; (3) to do work in uplifting the salt against gravity; (4) to do work in uplifting the aureole of uplifted sediments against gravity; and (5) to overcome friction within the sediments of that aureole. The quantity of energy available should vary from region to region; if the normal sediments are composed largely of limestone, the available energy should be larger than if the normal sediments are composed of moderately consolidated sands, sandstones, and shales; and much larger than if the normal sediments are unconsolidated sands, clays, and shales. The available energy may be (1)

sufficient to overcome friction and to do the work against gravity; (2) sufficient to overcome friction but not to do the work against gravity; and (3) insufficient either to overcome friction or to do the work against gravity.

If the available energy is sufficient to overcome friction and to do the work against gravity, actual upthrust of the salt core in earth space can take place.

If the available energy is sufficient merely to overcome the friction, actual upthrust of the salt core in earth space can not take place. If the mother salt bed and the sediments above it are stationary or rising in earth space, flowage of the salt can not take place and the salt dome can not grow. For example, a horse may be able just to overcome the rolling friction between a loaded wagon and the road; and the horse then will be able to move the loaded wagon on a level stretch of the road but will be unable to pull it up the slightest rise; that is, his strength may be sufficient to overcome friction but not to overcome friction and raise the wagon and load against gravity. Similarly, the energy available for upthrust of the salt core may be sufficient to overcome the friction involved in the flowage and upthrust of the salt core but may be insufficient to lift the salt and aureole and cap of uplifted sediments against gravity. But if the mother salt bed and the overlying sediments are subsiding in earth space, the salt core may grow by downbuilding of its base without actual uplift of any salt or sediments against gravity, for then there will be no work done against gravity; and all the available energy can be used to overcome friction.

DOWNBUILDING

Downbuilding of a salt dome superficially is much like upthrusting, excepting in reference to the relation of the salt dome to earth space; the flowage of the salt and the successive geometrical forms of the salt dome are essentially the same under the two theories. But in theory of upthrust of the salt, the base of the salt core is regarded as stationary and the crest is regarded as uplifted, whereas in the theory of downbuilding, the crest of the salt core is regarded as stationary and the base is regarded as moving downward. Mechanically, the two methods of formation of the salt dome are fundamentally different.

Downbuilding of the salt core will seem to many more plausible if it is viewed as concomitant upthrust of the salt from a sinking mother salt series. Actually, it is the sediments which move, and not the salt core. The energy requirement, however, is very much less than if there were actual upward movement of the salt.

The theory of downbuilding postulates that, in considerable part, the salt core has tended to remain constant in depth, while the sediments have sunk downward past it; and that concomitantly with the general subsidence of the whole sedimentary section, horizontal flowage of the salt from the area around a salt dome into the roots of the dome has tended to build the base of the dome downward in reference to earth space and in reference to the surface and, thereby, has tended to maintain the salt core constant in vertical position, in spite of the general subsidence. The process is presented diagrammatically in Figure 1.

The top of the basement, *JK*, of the salt series subsides to a new position, *J'K'*; the surface is maintained at a constant level by continuous deposition of the sedimentary material. But any bed, *LM*, sinks concomitantly with the subsidence of the basement, *JK*. The

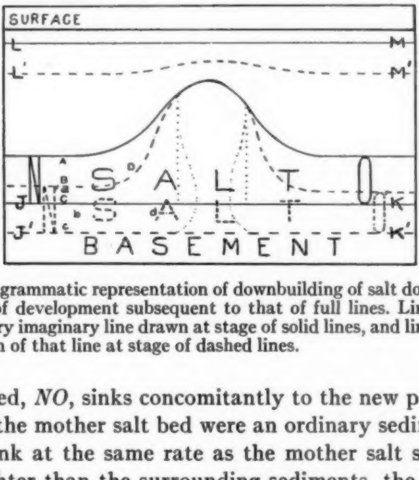

FIG. 1.—Diagrammatic representation of downbuilding of salt dome. Dashed lines represent stage of development subsequent to that of full lines. Lines of single dots represent arbitrary imaginary line drawn at stage of solid lines, and lines of double dots represent position of that line at stage of dashed lines.

mother salt bed, *NO*, sinks concomitantly to the new position, *N'O'*. If the salt of the mother salt bed were an ordinary sediment, the salt core would sink at the same rate as the mother salt series. But, as the salt is lighter than the surrounding sediments, the salt core of a dome by its buoyancy tends not to sink with the surrounding sediments. Under the pressure of the overlying sediments the plastic salt of the mother salt bed is forced to flow inward under the base of the salt core and thereby tends to build the root of the dome downward in earth space and in reference to the surface. The movement of the salt should not wholly be horizontally inward from the mother salt bed. The flaring flanks concomitantly should be pressed down and the salt of the flanks should flow plastically downward and slightly inward. The dotted vertical line in Figure 1 represents an assumed

vertical straight line in the salt at the stage of the solid lines. The corresponding curved line of double dots shows the position to which that line should have moved by the time of the stage of the dashed lines. This downbuilding takes place concomitantly with the subsidence of the basement and must cease when the subsidence ceases. The rate of flowage of the salt into the roots of the dome presumably approaches zero (1) as the thickness of the mother salt bed approaches zero, (2) as the salt and sediments approach isostatic equilibrium, and (3) as the rate of subsidence decreases. The continuance of the flowage of the salt and of the downbuilding is not dependent, however, on the continuance of deposition of new sedimentary material, although the cessation of that deposition may affect the rate of flowage slightly.

The relative uplift of the sediments around and over a salt dome which has grown by downbuilding, is produced by the greater subsidence of the sediments farther out from the dome. The sediments above and around the salt dome are supported or partly supported by the salt and friction with it. The salt, by its buoyancy, maintains its position in earth space, in spite of the postulated general subsidence. As those sediments can not sink as much as the sediments farther from the dome, they are left rising above those other sediments and simulating upthrust.

Upthrusting and downbuilding of a salt dome are not mutually exclusive. If the available energy is sufficient both to overcome friction and to uplift the salt plus the aureole and cap of uplifted sediments against gravity, and if the basement of the mother salt bed is sinking in earth space, upthrust and downbuilding of the salt core should take place simultaneously. It is conceivable, also, that the small salt domes in an area may grow only by downbuilding, and that the large domes in the same area may grow both by upthrust and downbuilding; for the external friction between the salt and the sediments per volume of uplifted salt is less in a salt dome of large radius than in one of small radius; therefore, the energy requirement for friction per unit volume of salt is less in a salt dome of large diameter than in one of small diameter. That small difference in the energy necessary to overcome that external friction could be sufficient to preclude upthrust of the salt on a salt dome of small diameter and yet permit it on a salt dome of large diameter.

If the available energy is insufficient to overcome friction, the salt dome can not grow and the whole system will remain frozen and fixed in reference to the sediments. If a salt dome has been partially formed, it will remain stationary and fixed in reference to the sediments which enclose it, and it will rise, stay fixed, or sink, in reference to earth

space respectively as those sediments rise, stay fixed, or sink in reference to earth space.

BIRTH OF A SALT DOME

The general, prerequisite conditions necessary before the formation of a salt dome can start are: first, that the mother salt bed lie below the critical minimum depth above which the salt could not flow with reasonable geologic speed under the existing conditions of temperature, pressure, water content of the salt, and composition of the salt series; second, that there is relatively decreased pressure upon the mother salt bed, or relatively decreased resistance to its upwelling in reference to the overlying sediments, at some place or along some zone; and third, that, if downbuilding is to form the dome, the basement of the mother salt bed and of the overlying sediments must be sinking in earth space.

The special conditions which will produce the necessary relative diminution of pressure on the mother salt bed, or the necessary dimition of resistance to the upwelling of the salt, or both, are speculative, if we postulate the static weight of the overlying sediments as the sole motivating force. Diminution of pressure will be found: (1) along the crests of folds which affect the salt series or the immediately overlying sediments, (2) along zones of faulting and fracturing which extend through overlying beds, to the top of the salt, (3) on considerable convexities on the top of the salt, and particularly along lines of incipient tensional rupture, and (4) along very deep canyons, as the Grand Canyon of the Colorado.

Tensional rupture of sedimentary prisms, according to Seidl,[5] should exhibit similar phenomena to those of the rupture of test plates under tension in the engineering laboratory. If a test bar or test plate is stretched slowly almost to the point of failure, the incipient break will start as a constriction in some transverse plane; and in the formation of the constriction, the lower surface of the bar and all lower zones in the bar will be bent up; and the upper surface and upper zones will be bent down. The prism of sediments above the mother salt bed might act as a huge bar or plate; and, if tension should produce incipient rupture along some vertical plane, that plane would be a zone of greatly reduced pressure on the mother salt bed. Seidl's argument leads logically to the possibility, not necessarily probability, also of downthrust of salt domes into the basement below the mother salt bed for, if that basement below the mother salt bed is the bar or

[5] Erich Seidl, *Bruch und Fliess-Formen der Technischen Mechanik und ihre Anwendung auf Geologie und Bergbau*, Band III (Berlin, 1930).

plate which is at the point of incipient rupture under tension, the decrease of pressure would be downward and the plastic salt should flow downward into the yawning constriction in the top of the basement.

MORPHOLOGY OF SALT DOMES

The form of the salt dome should tend to go through a characteristics series, or perhaps two characteristic series of forms.

Horizontal plan.—The initial plan of the dome should reflect the plan of the place or zone of weakness at which the salt domes start. But external friction will be least for a cylinder or core of circular horizontal cross section; and with increasing distance of intrusion of the salt core through the sediments, the salt core will tend to become more and more circular in cross section.

Vertical cross section.—Two types of series of vertical cross section of the salt core seem possible. (1) If the place or zone of weakness, or of diminished pressure at which the formation starts, is sharply and abruptly defined, and if the beds which more or less immediately overly the mother salt bed are more or less competent, the salt should tend to squirt up like tooth paste out of its tube; and the salt core should tend to be a cylinder; ultimately, when the flowage of salt from the mother salt bed into the root of the salt dome ceases, the lower part of the salt core should tend to be pinched off, unless the friction freezes the salt core to the sediments and precludes further movement. (2) The variation in the pressure on the mother salt bed, and in the resistance to the upwelling of the salt, may be gradual from the places of maximum pressure and resistance to the places of minimum resistance and pressure. The formation of the salt domes or ridges may start (1) as a thickening of the mother salt bed into broad flat domes or ridges in the areas of lesser pressure and resistance to upwelling and (2) as concomitant, equivalent thinning of the mother salt bed in the adjoining areas. The form of the salt core, therefore, should tend to go through the successive series of shapes which are shown in Figure 2. According to the theory of upthrust, the weight of the sediments which overlie the mother salt bed and base of the flanks of the dome, tends to produce upthrust of the salt of the central part of the dome, and of the upper part of the flanks. Under the theory of downbuilding, the salt of the central part of the dome, and of the upper part of the flank, tends to remain stationary as the sediments settle past it; and the salt of the lower part of the flank and salt from the mother salt bed tend to be forced inward under the base of the salt core and to build it downward.

Form in old age.—The old age form of the salt dome should be that of a stream-lined cylinder with nose upward; and the salt dome should be surrounded by a rim syncline in the upper beds. Most sediments at great depths must have a considerable degree of plasticity. The more brittle beds should tend to yield diagonally along fractures and shear planes. The static thrust of the overlying sediments, therefore, should have a diagonal downward or horizontal component against the flank of a relatively upthrust salt core. That diagonal and horizontal component of the thrust should tend to force the flank of the salt core inward and downward, and to force the latter into the form of a stream-lined cylinder pinched off from the mother salt bed

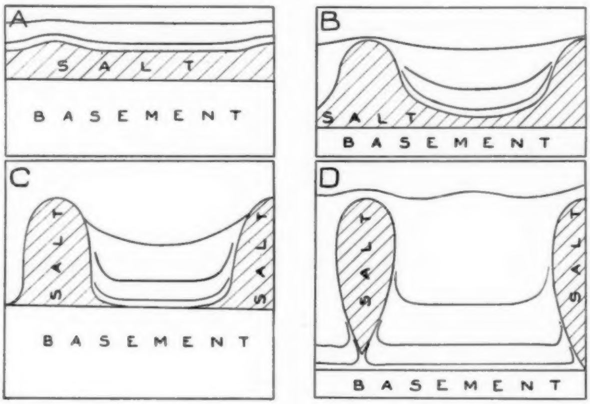

FIG. 2.—Evolution of form of salt dome: *A*, youth; *B*, early maturity; *C*, late maturity; *D*, old age.

below. That stream-lined form will produce the minimum of friction in the piercement of the sediments by the salt core.

Decadence.—Cessation of relative movement and decadence should conclude the old age of a salt dome. The horizontal pressure of the sediments against the stream-lined cylindrical salt core in old age should compress and elongate the salt core. The frictional resistance to the relative movement of the salt and the sediments increases with the increase of the surface area of the salt in reference to the volume. That increase will take place if the salt core is elongated without increase of volume. Ultimately the frictional resistance to the relative movement should become greater than buoyant upward tendency. The salt core will become frozen to the sediments and will remain stationary in earth space, if they are stationary, and sink with them if

they sink. Decadence of the salt core by solution should then set in. Solution by diffusion must take place whether or not the water around the salt dome is entirely static. Solution by diffusion is extremely slow, but should become considerable over the long periods of geologic time. Solution should be more rapid, if there is any circulation of water. The salt core ultimately will waste away under the effects of the solution.

Rim synclines.—A rim syncline in the upper sediments should be produced in the process of evolution of that ultimate stream-lined form of the salt dome. As the lower flank of a flaring salt core is pushed back under the salt core, the displaced salt must be replaced by sediments. The movement of those sediments should be downward or should have a large downward component and should be at a maximum over the flank. The deeper flank beds have a steep dip away from the salt core; therefore, that subsidence will not produce a syncline in them. The beds at shallow depth at the start will be horizontal or will be only faintly dipping over the flank; the subsidence will, therefore, produce a syncline in them. If the land surface is old or is the result of long erosion, the syncline should be best developed in the uppermost beds and should die out gradually downward in the face of the increasing normal dip of the beds with increasing depth.

A rim syncline of slightly different type and a central depression in the sediments should form as the result of the solution. The latter should tend to take place at right angles to the surface of the salt, except as relatively dry or impervious rock such as the anhydrite cap protects it. The vertical extent of the solution will be greatest immediately over the vertical edge of the salt and least over the center of the dome. The solution of the sides and top of the salt core will produce a syncline concentric with the salt dome. The greater vertical solution at the edge will produce a subsidiary synclinal trough or rim syncline immediately above the edge of the salt. The rim syncline of the preceding paragraph should be axial over the lower flank, whereas the solution rim syncline should be axial over the vertical edge of the upper part of the salt core. With the complete wasting away of the upper part of the salt core, that rim syncline will develop into a central syncline.

LIMIT OF UPTHRUST

Isostatic compensation of salt core.—The attainment of isostatic compensation should limit the maximum upthrust of the salt core, although friction must retard, and may preclude, its attainment. Small forces applied throughout the great lengths of geologic time com-

monly produce considerable effects; but friction may hold a body fast indefinitely, unless the force working against friction exceeds some minimum magnitude. The effects of friction should be considerable; the external and internal friction presumably can not be completely overcome; therefore, complete isostatic compensation presumably can not be attained.

Isostatic compensation of salt dome.—Distinction must be made between the isostatic compensation of the salt core alone and that of the salt dome as a composite system of salt core plus uplifted sediments. The salt in some degree supports or is frozen by friction to uplifted sediments; and in some proportional degree, the sediments will affect the maximum upthrust and attainment of isostatic equilibrium by the dome. If the salt core were firmly bound to the uplifted sediments, it would not be able to attain its isostatic equilibrium, and the maximum upthrust would be reached when the system (salt core plus uplifted sediment) attains isostatic equilibrium with the normal sediments. If the salt core were not bound at all by friction and were supporting no uplifted sediments, the salt core could attain its own independent isostatic equilibrium—but that assumption is impossible, for then the uplifted sediments would have no support. Practically, therefore, isostatic equilibrium of the salt should be unattainable. Upthrust of the dome as a whole will of course cease at the attainment of isostatic equilibrium of the system salt core plus uplifted sediments; upthrust of the salt core may continue, in so far as friction with and support of the sediments permits, but must cease before the attainment of its independent isostatic equilibrium.

Effect of size of dome.—Greater upthrust should be shown by domes of large diameter than by domes of small diameter, for two reasons: (1) the width of the aureole of uplifted sediments should not be much greater on a dome of large diameter than on one of small diameter; the ratio of the volume of the uplifted sediments to the volume of the salt should not be so large on a dome of large diameter as on one of small diameter; therefore, the buoyancy of the large dome should be greater than that of the small dome; (2) the external friction between the salt core and the sediments should be less per volume of salt on a dome of large diameter than on one of small diameter. A salt core of large diameter, therefore, should get closer to its position of isostatic equilibrium than should one of small diameter.

Effect of character of sediments.—The positions of isostatic equilibrium and of maximum upthrust should vary with variation of the character of the sediments through which the salt core has been upthrust. The buoyancy of the salt depends upon the difference between

the respective specific gravities of the salt and the sediments. The specific gravity of unconsolidated sands and clays is less than that of indurated shales and sandstones; and the specific gravity of the latter is less than that of limestone. Paleozoic sediments in general are denser than Mesozoic sediments and Mesozoic sediments than Tertiary sediments. Pliocene to Recent sediments may have a lower specific gravity than the salt; and the buoyancy of the salt intruded into those sediments will be negative. Salt domes should tend to be upthrust closer to the surface or farther above it in those areas in which the salt pierces sediments of the higher specific gravity.

Isostatic compensation versus downbuilding.—A salt core growing wholly by downbuilding can not attain isostatic compensation. By assumption, the force which tends to upthrust the salt is sufficient merely to overcome friction and not to do any additional work in uplifting the salt and sediments against gravity. The top of the salt core must stay fixed in earth space, except as epeirogenic uplift raises both

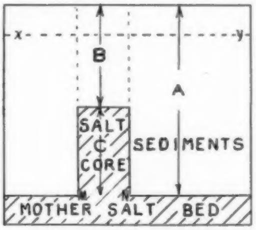

FIG. 3.—Diagrammatic representation of salt dome as simple system composed only of uplifted salt core.

salt core and surrounding sediments. The salt core should be able to maintain uplift which it has gained through the epeirogenic uplift; but presumably few salt domes have been produced wholly by downbuilding; and most salt domes should be nearer the position of isostatic equilibrium than if they had grown wholly by downbuilding.

VARIATION OF MOTIVATING FORCE WITH GROWTH OF DOME

Salt core alone.—The intensity of the motivating force which produces salt domes should vary progressively through development of the salt dome. That force in its simplest analysis is the difference $[A-(B+C)]$, as shown in Figure 3, between (1) the downward thrust, A, on the mother salt bed of the normal sediments above the mother salt bed and (2) the downward thrust on the mother salt bed at MN of the prism of sediments, B, plus the salt core, C. Upthrust of the

salt core in general involves the lengthening of C at the expense of B and the replacement of sediments by lighter salt. The downthrust of $B+C$ and the relative difference between the downward thrust of A and of $B+C$ must increase with upthrust of the salt core. But above some level, xy, the salt will be heavier than the surrounding medium, which may be the air, if xy is coincident with the surface; or which may be soft, unconsolidated, relatively light sediments. The downthrust of the prism of $B+C$ then will increase with progressive upthrust of the salt core above the level, xy. When a salt dome starts to form, the downthrust of B, by assumption, must be slightly less than that of A; that of C must be zero or nearly zero; and the intensity of the motivating force which produces the salt dome will be at some minimum value. It will increase to a maximum when the top of the salt core stands at the level xy; and then with continued upthrust of the salt core, it will decrease to zero when the position of isostatic compensation is reached. If the salt core grows wholly by downbuilding, the vertical dimensions of A and C increase equally; that of B remains constant; and the difference between the downward thrusts of A and of $B+C$ on the mother salt bed increases with the growth of the salt core; and as the specific gravity of sediments in general increases with depth, and as that of the salt increases only very slightly with depth, the rate of increase of the difference between A and $B+C$ should increase slightly with the downward growth of the salt core.

The motivating buoyant force of upthrust, therefore, may be sufficient to produce growth of the dome only by downbuilding during the earlier stages of the dome's existence; but, increasing with the downbuilding of the dome, it may become sufficient later to produce growth by upthrust as well. A dome in its youth, therefore, may be able to grow only by downbuilding; but in its old age or late maturity, it may be able to grow by upthrust.

Salt core plus uplifted sediments.—The law of the variation of that motivating force with growth of the salt dome is more complicated, if the aureole of uplifted sediments is included in the calculations. That force, then, is the difference between (1) the downward thrust of A (Fig. 4) of the normal sediments, and (2) the downward thrust of the salt core, C, plus the prism of sediments, B, above the salt core, plus the extra weight of the aureole of uplifted sediments, D, which have a slightly higher specific gravity than the normal sediments at the same level. The downward thrust of the system, $B+C+D$, decreases with the growth of C and with the equal decrease of B, and increases with the growth of D; C and D grow proportionally but not

necessarily at an equal rate. The over-all resultant variation of the system, $B+C+D$, will depend on the relative variation of the effects of C and of D; that variation should be different under different conditions and should depend on several factors: the specific gravity of the sediments; the variation of that specific gravity with depth; the size of the dome; the flare of the sides; the width and the degree of upthrust of the aureole of uplifted sediments; and the friction between the salt core and the sediments. The variation of the effects, C and D, may be the same, or different. The intensity of the motivating force which produces the salt dome accordingly may stay constant during the growth of the dome, or may decrease, or increase, continuously from the start of the dome to the attainment of isostatic compensation. The effect of the factor D, the aureole of uplifted sediments, should start from zero on the incipient dome; and after reaching a maximum during the mature stage of a dome, it should decrease to a second minimum which should not be zero and which may be high, when the salt core reaches the old-age form of the stream-lined cylinder.

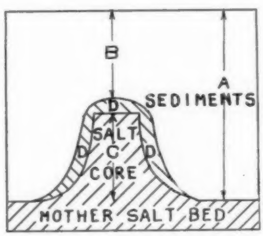

FIG. 4.—Diagrammatic representation of salt dome as system composed of salt core and uplifted sediments.

Map plan of occurrence of salt dome.—The occurrence of the domes should reflect the plan of the salt basin, or basins, of thickening of the salt within a basin, and of the structural, or other, lines and places of weakness along which, or at which, the salt domes started. Fault and fracture zones commonly show a pattern of parallel lines or of intersecting sets of parallel lines. A salt dome forming along a single fault or along a fracture zone may be elongated along the fault or fracture zone; and its elongation will not be an indication of the effect of horizontal thrust in the direction of the transverse axis of the dome. The point of intersection of faults of different sets, or of fracture zones of different sets, or of faults with fracture zones, should be points of especial weakness; and there may, therefore, be a tendency for align-

ment of the salt domes along cross trends. But a single fault, or a single fracture zone, rarely is continuous for a long distance; commonly, it dies out; and another starts up, slightly *en échelon*. Considerable irregularity, therefore, will be introduced into that plan of cross alignment of the domes. But in spite of any tendency toward alignment, the domes should be more or less uniformly spaced throughout the whole area of the thick salt deposit, for the motivating force under the theory of the formation under the static downward thrust of the sediments above the salt is essentially uniform throughout the whole area.

FORMATION OF DOMES BY TANGENTIAL COMPRESSION

The tangential compression of orogenic movements should produce the necessary differential pressure to induce flowage of the salt and the formation of salt domes. But static downward thrust of the sediments which overlie the mother salt bed will contribute to total pressure which is acting on the salt and which is producing the salt domes.

Tangential pressure which tends to induce merely simple horizontal shortening of a mother salt formation of uniform thickness will not effect or affect the formation of a salt dome. The upward thrust which will be transmitted through the plastic salt will act equally against the downthrust of the sediments, *A*, of Figure 4, and the downthrust of the prism of the salt core plus overlying sediments plus the aurole of uplifted sediments and, therefore, will cancel out of the equation of the difference of the two downthrusts.

Horizontal thrust in effecting and affecting the formation of salt domes should act in two ways: (1) through the effect of folding which it produces in competent beds above the mother salt bed, and (2) through direct horizontal pressure on the salt which has been arched up in the cores of anticlines, or which has been relatively upthrust in the cores of salt domes.

Transmission of thrust by growing folds.—The actively growing folds in competent beds will transmit a component of the motivating horizontal thrust: downward in the synclines, and upward in the anticlines. Differential downward pressure on the mother salt bed will be produced thereby, if the competent bed lies above the mother salt bed. That differential pressure is assumed to be pressure which is derived wholly through transmission by the competent bed of the horizontal thrust. An additional differential pressure will be produced by the static downward thrust of the overlying sediments; a part of the downward thrust of the sediments upon the anticline will be trans-

mitted to the syncline by the arch in the competent bed. This latter effect will be the same, whether the folding is going on, or has ceased. The effect of each of these two differential pressures will be to produce flowage of the salt from the synclines into the anticlines. It is possible to have the static differential pressure, without dynamic differential pressure. But it is not possible to have the dynamic differential pressure without the static differential pressure.

Effect on salt cores.—Horizontal pressure will be exerted on the opposing flanks of salt cores of domes or anticlines by the tangential, horizontal thrust and will tend to squeeze the salt of the core. The effect of that horizontal pressure on the salt core will increase with the steepness of the flanks of the core and with its vertical length; the effect should be negligible on very flatly arched domes or anticlines; and it should be at a maximum on the elongated vertical salt cores of diapirs. The horizontal pressure will be partially transformed by the salt into a pressure upward and a pressure downward within the salt. Downward flowage of the salt theoretically would be possible, if the beds above the top of the salt core, and those in contact with the flank of the salt core, gave sufficient resistance to further relative upthrust, and if the downward component in the salt of the force of horizontal compression were sufficient to overcome friction and to uplift the prism of sediments overlying the mother salt bed. But, in general, the direction of easiest relief of the pressure should be upward; and the general tendency should be to squeeze the salt upward. Elongation of the salt core horizontally at right angles to the direction of the tangential compression also should be produced.

Position of maximum uplift.—The maximum elevation to which the salt core can be upthrust is not necessarily that of its position of isostatic equilibrium, but may be far above it. If the salt core were in direct connection with the mother salt bed, and if there were no friction, then the salt core could not rise above the position of isostatic equilibrium. But if friction and other resistance to upward squeezing of the salt of the salt core is less than the friction and other resistance to the squeezing of the salt of the salt core downward and back into the mother salt bed, then the salt core and the dome as a whole can be thrust up above the position of isostatic equilibrium. The situation is clearest for the case of a salt core which has been pinched off and wholly separated from the mother salt bed. The pinched off, upper segment of the salt core will be enclosed in a space which is rigidly confined in reference to downward movement or in reference to much horizontal movement relative to the sediments. Under dynamic horizontal thrust, the salt core will be squeezed upward like a wedge from

the jaws of a closing vise and may be upthrust far above the position of isostatic equilibrium. The same effect may be obtained in a salt core of small horizontal cross section and of large vertical length; the resistance of friction and of the buoyancy of the salt to downward movement may freeze the lower half of the salt core; and the tangential compression then can squeeze the upper part of the salt core up far above the position of isostatic equilibrium. In areas in which tangential compression may have been effective in the upthrust of the salt domes, salt cores which rise high above the general level of the surface, such as those in Persia, should not be assumed necessarily to be in isostatic equilibrium; without further analysis of the possible effect of the force of tangential compression, such domes should not be adduced as evidence of the power of the buoyancy of the salt to produce the upthrust of the salt domes; and the magnitude of the rise of the salt core of such domes above the general level of the area should not be used with the assumption of isostatic equilibrium to calculate the approximate vertical length of the salt core. It is, of course, possible that a massive limestone or limestone-anhydrite section might produce sufficient buoyancy to explain the great upthrust of many of the Persian salt cores above the general surface level, but, on the other hand, the salt domes lie in front of a great overthrust and, therefore, the influence and results of the tangential thrust must be considered carefully in any discussions or calculations in regard to the formation of those salt domes.

Morphology.—The form of "dynamically" produced salt domes should show a varied range of types. Elongation in the horizontal direction perpendicular to the direction of unilateral tangential thrust is characteristic of structures which are produced by such thrust, and should be characteristic of the "dynamically" produced salt domes. The form of such folds and overthrust varies greatly with special conditions: of the character of the sedimentary section and particularly of the competence of the beds; of the intensity of the tangential thrust; of the intensity of the compression and the intensity of the resultant folding and overthrusting; and of the way in which the tangential thrust is applied, as, for example, in the nut-cracker action of two competent blocks on an incompetent intervening basin, or the overthurst (or underthrust) of a competent block against a large block of incompetent sediments. The "dynamically" produced salt domes should show a corresponding variation in form. If the folding is gentle and there is a thick upper section of very incompetent sediments, the forms of domes in maturity and old age should approach the forms of domes which have been produced wholly by the static thrust of the

weight of the sediments. The salt cores, however, may be slightly flattened in the direction of the horizontal thrust, particularly in their roots, will rise out of deep anticlines, and are more likely to be pinched off in depth than are the "statically" produced domes.

If the folding is gentle and if there is a moderately thick cover of moderately competent, not too brittle, sediments, the salt structures should have the form of salt anticlines. The salt cores may arch but not pierce the overlying sediments or may pierce them slightly.

If the folding is intense, the salt should be squeezed hither and yon, from the place of maximum pressure between blocks pressing hard against one another, along fault planes, fracture zones, through fissured crests of anticlines, in general upward, but in whatever direction there is less pressure and in which adjacent blocks press less hard against one another. The forms which the salt body may assume will be infinite in variety and the individuality of the salt dome as a special structure may be lost in the general complexity of the structure of the area.

After the cessation of the dynamic horizontal thrust, further growth of the domes will be according to the laws of growth of domes under the static thrust of the weight of the overlying sediments. The form of the salt core and dome should tend to become more like that of a "statically" produced dome, but the form which they inherit from their "dynamic" past, and the folded and overthrust sediments in which they lie, will affect the form of the salt core and dome. The salt core may be intruded relatively upward into a thick series of sediments which have been deposited since the cessation of the tangential dynamic thrust. Within those overlying unfolded sediments and with progressive intrusion upward into them, the salt core and salt dome will tend progressively more and more to assume the form of a "statically" produced dome and to lose the traces of their "dynamic" past.

Map plan of occurrence of salt dome.—The map of the arrangement of the domes should reflect the special conditions of the tangential thrust. The general plan in all cases should be alignment of the domes and elongation of the domes in the horizontal direction perpendicular to the direction of thrust or tangential compression. If the tangential compression is produced by the thrust of a competent block horizontally against a thick section of generally incompetent beds which are of wide extent parallel to the direction of thrust, the thrust will be taken up by compression, overthrusting, and folding of the sediments, and will decrease rapidly outward from the front of the competent block in the direction of the thrust. The effect of

the thrust in the formation of the salt domes, therefore, should decrease outward away from the front of the competent block. In old Roumania, the salt of many of the salt domes in the zone of the overthrusting, for example, Slanic-in-Prahova, come to the surface or very close to the surface. In domes such as Moreni and Tintea, immediately in front of the overthrust, the salt comes almost to the surface. At Moldesti, one of the domes which lies farthest out in the Roumanian plain, the salt is deep. If a relatively thick, fairly competent member is included in the thick, generally incompetent section of sediments, the thrust will be transmitted through that relatively competent member with a relatively slow decrease in intensity outward from the front of the thrust block. The intensity of the effects of that thrust in the formation of salt domes will decrease relatively slowly outward from the front of the thrust block. If a relatively narrow sedimentary basin lies between two relatively rigid blocks and if one block is being thrust against the other, the thrust will be transmitted approximately uniformly across the basin; and the intensity of the effects of that thrust in the formation of salt domes will be approximately uniform across the basin. The variation of the intensity of the thrust will be reflected in variation of the growth of the salt domes.

Dynamic folds and dynamic tangential thrust versus static downward thrust of sediments.—The static downward thrust of the overlying beds on the mother salt bed, the buoyancy of the salt core in reference to the surrounding sediments, and the negative buoyancy of the uplifted sediments must have essentially the same influence and effect in the formation of salt domes whether dynamic horizontal thrust also is tending to effect the formation of salt domes, or whether such thrust is entirely absent. The beds which overlie the mother salt bed have the same weight and produce the same downthrust whether or not they and the whole system are under horizontal dynamic thrust. There is a bare possibility that the crest of a nascent anticline might underlie a position of maximum downward static thrust of the overlying sediments and an accompanying nascent syncline might underlie the position of minimum downward static thrust of the overlying sediments; and through its production of that folding, the dynamic, horizontal thrust might counterbalance or overbalance the differential static downward pressure of the sediments, and start the formation of the salt dome at the place where it would be least likely to form under conditions of simple static downward thrust, and might prevent the formation of a salt dome at the place at which it would have formed. If the salt core of an anticline rises above the mother

salt bed or above the salt in the adjacent synclines, the differential static pressure between (1) the static downward thrust of the overlying sediments on the mother salt bed or the salt in the syncline, and (2) the static downward thrust of the overlying beds on the crust of the salt core, should be the same whether or not the anticline and syncline are growing actively as the effect of the horizontal dynamic thrust. That differential pressure, however, will not be the same as there would be if the anticline were not present; for, if the beds immediately above the salt were perfectly competent, the arch of the anticline would (1) carry the whole weight of the prism of sediments above the salt core, (2) transmit it to the adjacent synclines, and (3) wholly relieve the static downward pressure on the top of the salt core. Even if the beds above the salt are only slightly competent, the arch of the anticline will divert part of the static downward thrust of the prism of sediments above the salt core from the top of the salt core to the adjacent synclines or to the adjacent parts of the mother salt bed. The change in the arch of the anticline with the passage of time and the growth of the anticline will produce a change in the diversion of the static downward thrust from the top of the salt core to the adjacent synclines or to the edge of the mother salt bed; but at any particular moment, the differential static thrust will be the same, whether or not the anticline is growing actively as the effect of the horizontal dynamic thrust.

The total differential pressure between the downward thrust on the top of the salt core and the downward thrust on the mother salt bed or on the salt in the adjacent synclines will be greater by a dynamic component, if the anticlines and synclines are growing actively as the effect of the horizontal, dynamic thrust. The differential dynamic pressure between the downthrust in the syncline and the upthrust on the anticline must vary with the particular case and must be difficult of estimation for any particular case. Presumably, it must, in general, be relatively small compared to the static differential pressure, unless the mother salt bed is fairly shallow and overlain by fairly competent beds, or unless the folding is intense. Except in those special cases, the static downward thrust of the sediments above the salt must be fully as important, or more important, than the dynamic thrust in effecting the formation of the salt domes. But, if the salt core has been pinched off, the thrust of the overlying sediments on the mother salt bed and the buoyancy of the salt of the lower pinched-off segment of the salt core will no longer be a factor in the upthrust of the upper pinched-off segment of the salt core. The buoyancy of that upper segment continues to be a factor in its further upthrust;

but the specific gravity of the sediments rather commonly decreases upward and in the upper beds may become equal to or less than the specific gravity of the salt; the buoyancy of this upper pinched-off segment of the salt core, therefore, may be small, zero, or negative, and should be relatively unimportant in effecting the further upthrust of that segment, unless the segment extends to very great depth or unless the surrounding sediments have a high specific gravity. That upper pinched-off segment will be in the position of a wedge in the jaws of a closing vise, and further upthrust of the segment will depend mostly on the horizontal dynamic thrust.

RECAPITULATION

The thesis which has just been sketched in regard to the formation of salt domes briefly is the following.

The salt of the salt domes in some areas is known to be sedimentary.

Salt is known to flow plastically under differential pressure. The evidence comes from laboratory experimentation and from geological observations of salt series which have flowed.

The German salt domes are known to have been formed by the plastic flowage of the Zechstein salt series. By their similarity to the German salt domes, the salt domes of other areas presumably have formed by the plastic flowage of sedimentary salt series.

Differential pressure should produce plastic flowage of a sedimentary salt series, when certain critical conditions of pressure, temperature, water, and composition of the salt series have been attained or exceeded.

The plausible sources of pressure are two: (1) the static pressure of the weight of the sediments which overlie the salt, and (2) the dynamic pressure of tangential thrust. The first can occur without the second, but the second can not occur without the first. The formation or salt domes is produced when either exerts a differential vertical pressure on salt of sufficient volume and under the appropriate conditions of pressure, temperature, water, et cetera.

1. Under the conditions of the purely static pressure, the initial differential pressure is given by arching or warping of the surface of the mother salt bed or the overlying sediments, zones of fracturing or fissuring or faulting, zones of tensional stretching of the overlying prism of sediments.

After the partial upthrust of a salt core, the effective differential pressure will be the difference between the downward pressure of the normal sediments on the salt and the downward pressure of the prism of the salt plus uplifted sediments plus the overlying sediments.

If the energy which is available through that pressure is sufficient to overcome friction and to uplift salt and sediments against gravity, growth of the dome by upthrust will take place.

If the available energy is sufficient to overcome friction but not to overcome friction and to uplift salt and sediments against gravity, the dome may grow by downbuilding in a subsiding area.

If the available energy is not sufficient to overcome friction, growth of the dome can not take place.

Growth by downbuilding and by upthrust can take place simultaneously on the same dome.

The position of maximum uplift is below the position of isostatic equilibrium on account of the drag of friction and of negative buoyancy of uplifted sediments.

The form of the dome should evolve through a characteristic series of forms progressively with its growth.

2. Under the conditions of dynamic unilateral horizontal thrust, the dynamic horizontal thrust will act on the salt: (1) through downward pressure in growing synclines, and through upward release of pressure in growing anticlines, in competent beds; and (2) through direct horizontal squeezing of the salt in relatively upthrust cores.

The static vertical thrust of the weight of the overlying sediments will be present, and by the differential distribution of its thrust on competent arches, it may be more important than the dynamic thrust. The position of maximum uplift may be far above the position of isostatic equilibrium on account of the squeezing action of the horizontal thrust on the upper part of the salt core.

The form of the domes should be notably varied but should show horizontal elongation perpendicular to the direction of thrust.

Part II

Formation of Gulf Coast Salt Domes

SEDIMENTARY SOURCE OF SALT

The only direct evidence of the sedimentary origin of the salt of the Gulf Coast salt domes is the presence of fossil algae[6] in the sylvite of a core from a depth of 4,804 feet in the Rycade Oil Corporation's Gray No. 1 at Markham, Matagorda County, Texas. Beds comparable with the marine gray salt clay within the Zechstein salt series of North Germany, or with the intercalated clays beds of the salt in the salt

[6] E. L. DeGolyer, "Discovery of Potash Salts and Fossil Algae in Texas Salt Domes," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 9, No. 2 (March–April, 1925), pp. 348–49; also *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol., 1926), pp. 781–82.

domes of old Roumania, have not been found in the salt of the Gulf Coast salt domes. An elongate sheet-like stringer of red sandstone is exposed in the Avery Island salt mine, Iberia Parish, Louisiana; it may be a sedimentary bed, but it does not show any conclusive evidence of its origin.

The volume of the salt of the salt cores of the domes is congruent with the theory of the sedimentary origin of the salt; the salt of those cores in the area of southeast Texas and southwest Louisiana is equivalent to approximately 700 vertical linear feet of salt over the whole area; several salt series of greater thickness are known in the world.

That quantitative estimate of 700 vertical linear feet of salt is obtained by the following calculations.

Area, which includes the domes from Sulphur, Calcasieu Parish, and Calcasieu Lake, Cameron Parish, Louisiana, on the east, to Hockley, Harris County and Markham and Big Hill, Matagorda County, Texas, on the southwest, 4,000 square miles

Shallow domes		
Small domes	Number	32
	Average area	1½ square miles
	Total area	50 square miles
Large domes	Number	9
	Average area	6 square miles
	Total area	60 square miles
Total area of shallow domes		110 square miles
Height of salt core above its base		3½ miles
Total volume of salt of shallow domes		400 cubic miles
Deep domes (known, surmised, undiscovered)	Number, possibly	20
	Average area	3 square miles
Total area of deep domes		60 square miles
Height of salt core above its base		2 miles
Total volume of salt of deep domes		120 cubic miles
Total volume of salt of deep and shallow domes		520 cubic miles

Five hundred and twenty cubic miles of salt spread uniformly over an area of 4,000 square miles would give a sheet of salt 690 feet thick.

The flowage of 700 vertical linear feet of salt from the area around the salt domes into the domes, therefore, would account volumetrically for the salt of the salt cores of the domes in southeast Texas and extreme southwestern Louisiana. The German salt beds have a thickness of about 1,000 feet in the Werra district, in which there are no salt domes; the stratigraphic thickness of the salt beds in the Stassfurt district is variously estimated to be between 1,200 and 2,100 feet, and in the Hannover district, 1,600 feet thick. The Permian salt beds of West Texas and southeastern New Mexico, according to Hoots,

have a thickness of more than 1,000 feet in an area of more than 10,000 square miles. The postulation of a salt series in the Gulf Coast with an original average thickness of approximately 700 feet, therefore, is in no way improbable in the light of the known sedimentary salt series.

AGE OF SALT

The stratigraphic age of the salt of the Gulf Coast domes is unknown. It must be older than uppermost Upper Cretaceous, for chalk of Navarro age has been brought up by the South Liberty dome, Chambers County, Texas. A definite identification of the Permian age of the salt was postulated by Powers[7] on the identification of seemingly identical algae in the red potash salt from Markham, Matagorda County, Texas, and in Permian salt from Kanopolis, Kansas, but Schuchert's objections that algae are long lived, that they are poorly preserved as fossils, and that they are poor criteria for determination of the age of the salt seem well taken.

A pre-Lower Cretaceous (Comanche) age, or at least basal Lower Cretaceous age may be postulated indirectly from the age of the salt of the interior domes. Basal Lower Cretaceous rests on the top of the salt at Smackover, Union County, Arkansas; Spooner[8] interprets the contact as unconformable and postulates a pre-Lower Cretaceous age for the salt. Glen Rose (lower Lower Cretaceous) has been brought up by the Boggy Creek dome, Anderson and Cherokee counties, Texas.[9] The age of the salt of the interior domes seems, therefore, to be earliest Lower Cretaceous or pre-Lower Cretaceous. There is no geologically logical necessity that the ages of the Gulf Coast salt and of the salt of the interior domes can not be different, but a common stratigraphic age seems much more probable. The age of the salt of the Gulf Coast domes, presumably, therefore, is pre-Lower Cretaceous, or at least as old as earliest Lower Cretaceous (Comanche).

A Permian age is ascribed to the salt by some geologists on account of the extensive Permian salt deposits in West Texas and on account of the somewhat common occurrence of salt deposits in the Permian throughout the world.

[7] Sidney Powers, "Interior Salt Domes of Texas," *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol., 1926), p. 218.

[8] W. C. Spooner, "Salt in Smackover Field, Union County, Arkansas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 601–07.

[9] H. G. McLellan, E. A. Wendlandt, and E. A. Murchison, "Boggy Creek Salt Dome, Anderson and Cherokee Counties, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 584–600.

The Lower Cretaceous sediments of the Gulf Coastal Plain include anhydrite and traces of salt. From that evidence and from paleogeographic evidence, Schuchert concludes that the salt can not be of Permian age but must presumably be of Lower Cretaceous age.

Salt of Early Paleozoic age extends southward down the Appalachian geosyncline as far as Saltville, Virginia; and at that place, is not much farther from the nearest Gulf Coast salt dome than the Permian salt is from the Gulf Coast salt dome nearest to it.

The presence of salt and anhydrite in the Lower Cretaceous does not necessitate the ascription of a Lower Cretaceous age to the salt of the salt domes. In Germany, there is salt of several ages other than Zechstein, although the salt of the major salt deposit and of the salt domes is Zechstein.

The evidence for a Permian age or for an early Paleozoic age is equally good, or poor. The actual status of our knowledge is merely that the salt is older than some time in early Lower Cretaceous and more than that we do not know.

MODE OF FORMATION

The structural relations of the flank sediments, and of the salt to the flank sediments, show that the salt core has been intruded stratigraphically upward into its present position. The flank beds dip quaquaversally away from the salt core. The steepness of the dip increases with increasing proximity to the edge of the salt. Radial and peripheral faults are common on the flank.

The salt domes of the Gulf Coast are very similar to Lüneburg, Benthe, and many other domes of the North German Coastal Plain. The salt domes of northern Germany are known to have been formed by the plastic flowage of the Zechstein sedimentary salt series. The similarity of the Gulf Coast domes to those German domes gives very strong contributory evidence that the Gulf Coast salt domes have been formed by the plastic flowage and intrusion of sedimentary salt relatively upward into the sediments in which the salt domes are now found.

AGE OF MOTIVATING FORCE IN GULF COAST

The force, or forces, which affected the formation of the Gulf Coast salt domes were active as early as Wilcox (early Eocene) time and must have continued into the very recent geologic past. The thinning of the Wilcox and later Eocene beds at Clay Creek indicates progressive relative upthrust of the dome through Wilcox and later Eocene time. The much greater deformation of the Jackson (latest Eocene)

beds than of the overlying Oligocene beds at Esperson, Chambers County, Texas, indicates considerable pre-Oligocene movement. The greater deformation of the Oligocene beds than of the overlying Miocene beds at Damon Mound, Sugarland, Arriola, indicates movement as late as the end of the Oligocene or the beginning of the Miocene. The projection of the many shallower domes into the Pliocene, or through the Pliocene into the Pleistocene, indicates post-Miocene, Pliocene, and Pleistocene movement. The greater mean slope of the base than of the top of beds in the top of the Pliocene (base of the Pleistocene?) at Bryan Heights indicates progressive movement concomitantly with the deposition of the beds. The deformation of Pleistocene beds which extend across above the top of salt domes indicates late Pleistocene to Recent movement. Such a salt-dome mound as that at Barbers Hill indicates post-Beaumont uplift; for an ancient Beaumont distributary of Trinity River flowed across the position which is now occupied by the 40-foot salt-dome mound; in the aerial photographic maps[10] of the area, the ancient meandering channel can be traced from the center of the mound across the north edge of the mound. The channel is trenched no deeper or more definitely on the mound than off it. The uplift of the mound, therefore, must have taken place after the stream ceased to flow. The mound of the Old Hackberry salt dome is cut by two antecedent channels which seem to belong to the present marsh drainage system; and the mound, therefore, must be post-Pleistocene. The mounds of the Avery Island, Weeks Island, Cote Blanche, and Belle Isle salt domes in Iberia and St. Mary parishes, Louisiana, rise 100–120 feet above the surrounding salt marsh; the mounds do not show the effects of marine erosion and, therefore, must be younger than the marshes which are of Recent age. Recent clays extend across the top of the Cote Blanche mound. The salt at Avery Island rises about 80 feet above the general level of the surrounding marsh and comes to a height within 20 feet of the surface of the mound; it would seem doubtful whether the salt spine could maintain itself long against solution under the moist climate of the area; the upthrust of the salt, therefore, must have been fairly recent or upthrust must be taking place to compensate solution. The motivating force or forces in the formation of the domes, therefore, must have continued active into Recent time.

Reliable instrumental proof of measurable modern movement of uplift is not available. Modern uplift at the rate of approximately 0.5 inch per year at Hoskins Mound has been postulated; good but not precise levelling of the Freeport Sulphur Company is reported to

[10] *The Oil Weekly*, Vol. 64, No. 10 (February, 1932), p. 17.

show uplift of the surface of the mound at that rate during the past few years; but geologically that rate of uplift is so large that more probably it should be attributed to the effects of the sulphur mining operations, in which superheated water is pumped into the cap rock under pressure. Re-survey by the United States Coast and Geodetic Survey in 1912 of a line of precise levels which was run by the United States Geological Survey into Weeks Island in 1906 showed no measurable movement of the benchmarks on Weeks Island compared with those on the rest of the line.[11]

The motivating force or forces which have produced the Gulf Coast salt domes must have been active practically throughout the Tertiary. The evidence available is not conclusive as to whether that force or those forces were active continuously or only spasmodically. But it seems definite that relative upthrust of the domes took place in the Eocene, in the Oligocene, in the Miocene, in the Pliocene, in the Pleistocene, in the post-Pleistocene, and in Recent geologic time. According to the writer's impression, the movement has been fairly continuous, but that impression is based merely on casual experience and not on a careful study of the question. Although it is impossible to say that the movement is going on at present, it has persisted so late into the recent geologic past that presumably it must still be taking place, and that presumably the force or forces which produced the domes in the past must still be present.

APPARENT UPTHRUST PRODUCED BY COMPACTION

Compaction of the sediments which overlie the mother salt bed produces and has produced apparent subsidence of those sediments, and apparent upthrust of the salt in reference to them.

Crude calculations indicate 3,000+ feet of compaction of the sediments above the mother salt bed. Quantitative calculations in connection with torsion-balance surveys of the salt domes in the Gulf Coast necessitate the assumption of increasing specific gravity of the sediments with increasing depth below the surface. The writer's standard assumption of the variation of specific gravity of the sediments with depth is:

Feet in Depth	*Specific Gravity*
0 to 500	2.0
500 to 1,000	2.1
1,000 to 2,000	2.2
2,000 to 4,000	2.25
4,000 to 6,000	2.30
6,000 to 10,000	2.35
10,000 to 20,000	2.40

[11] H. V. Howe and C. K. Moresi, "Geology of Iberia Parish," *Louisiana State Dept. Conservation Geol. Bull. 1* (1931), pp. 76–78.

The specific gravity of the salt is assumed to be 2.19 ± 0.03. The assumptions for the specific gravity of the sediments from depths above 4,000 feet are based in part on laboratory determinations which were made within one hour of the recovery of the core or bit sample from the well, and in part on the necessities of assumption in order to get the calculated gradient profiles to fit the observed gradient profiles. The assumptions in regard to the specific gravity of the sediments at the depths below 4,000 feet are based on theoretical deductions from the necessities of the calculations in connection with torsion balance surveys and from extrapolation downward of the decrease in density.

The total compaction which presumably is involved in the production of that increase of specific gravity with depth can be calculated, if the further assumptions are made that all the sediments originally had the same specific gravity as the sediments at the surface; that the average specific gravity of the constituent materials of the sediments is 2.6; and that the pore space in the sediments is filled with water of specific gravity 1.0. The pore space in the 0–500-foot zone will then be 38 per cent; and in the 10,000+ foot zone, 13 per cent. The reduction in the pore space is assumed to indicate compaction of the sediments; and the shrinkage of the sediments is assumed to take place in the vertical direction. Thus the compaction in the several zones has been as follows.

Zone in Feet	*Compaction in Feet*
500 to 1,000	50
1,000 to 2,000	150
2,000 to 4,000	390
4,000 to 6,000	470
6,000 to 10,000	1,160
10,000 to 15,000	1,700
Total	3,900+ or approximately 4,000

These figures are of value only in giving a very crude indication of the probable magnitude of the compaction.

The approximate rate of that compaction can be calculated crudely. The accumulation of the upper 15,000 feet of sediments above the mother salt bed is assumed to have been going on continuously at a uniform rate for 9 million years; the actual time probably is more than half, and less than twice, that figure. Compaction in each of the zones is assumed to go on continuously at a uniform rate. The compaction which has been attributed to the 500–1,000-foot zone may be assumed for the purposes of calculation to have taken place while the center of the block of sediments which now occupy the zone moved from a depth of 250 feet to a depth of 750 feet. If the further assumption is made that the present depth of the mother salt bed is 15,000

feet,[12] the time necessary for that movement will be $500/15{,}000 \times 9{,}000{,}000 = 300{,}000$ years; and the rate of compaction in the 500–1,000-foot zone then will be 17 feet per 100,000 years. The rate of compaction can be calculated in a similar manner for the lower zones. The rates of compaction per 100,000 years according to the writer's calculations are:

Zone in Feet	*Feet*	*Feet Per Thousand Vertical Feet*
500 to 1,000	17	39
1,000 to 2,000	10	10
2,000 to 4,000	9	4½
4,000 to 6,000	6	3
6,000 to 10,000	11	2¼
10,000 to 15,000	10	2

The total rate of compaction for the whole sedimentary column above the mother salt bed, according to those calculations and assumptions, should be 62 feet per 100,000 years. That figure, of course, has only a qualitative value. It is probable that the assumptions are accurate enough so that it is safe to say that the rate of compaction is more than 40 feet, and less than 140 feet, per 100,000 years. The rate of 62 feet per 100,000 years is the same as a rate of 1 foot in 1,600 years and should be sufficient to produce appreciable effects at the surface.

The effects of that compaction possibly can be seen in the present topography. The depth to the top of the salt or cap rock in the Gulf Coast salt domes shows a fairly definite plan (Fig. 5). The salt cores of the shallow salt domes should act as supporting pillars; compaction should be at a minimum in the areas of shallow domes; and the areas of shallow domes should be topographically higher than the areas of very deep domes. There is a suggestion of such an effect. Galveston Bay lies in the center of a large area of very deep domes. Sabine Lake and the Neches and Sabine rivers which empty into it lie in a trough of deep domes; Calcasieu River flows along the west flank of a broad area of very deep domes. The writer's so-called Iberian Peninsula of dry land extends down the axis of a prominent, linear zone of very shallow domes. The Mississippi River borders the northeast side of that Iberian zone of shallow domes. In southwestern Louisiana, a topographic ridge practically coincides in position with the line of salt domes which parallels the Southern Pacific Lines main line. The lack of compaction in the salt, and the lessened compaction in the flank sediments of the salt domes, may explain the connection of those topographic features with the depth to the top of the salt domes.

[12] Since those calculations were made, the writer has come to believe that the depth of the mother salt bed more probably is 20,000 feet at Houston, Texas; 25,000 feet at Jennings, Louisiana, and 30,000 feet south of New Orleans.

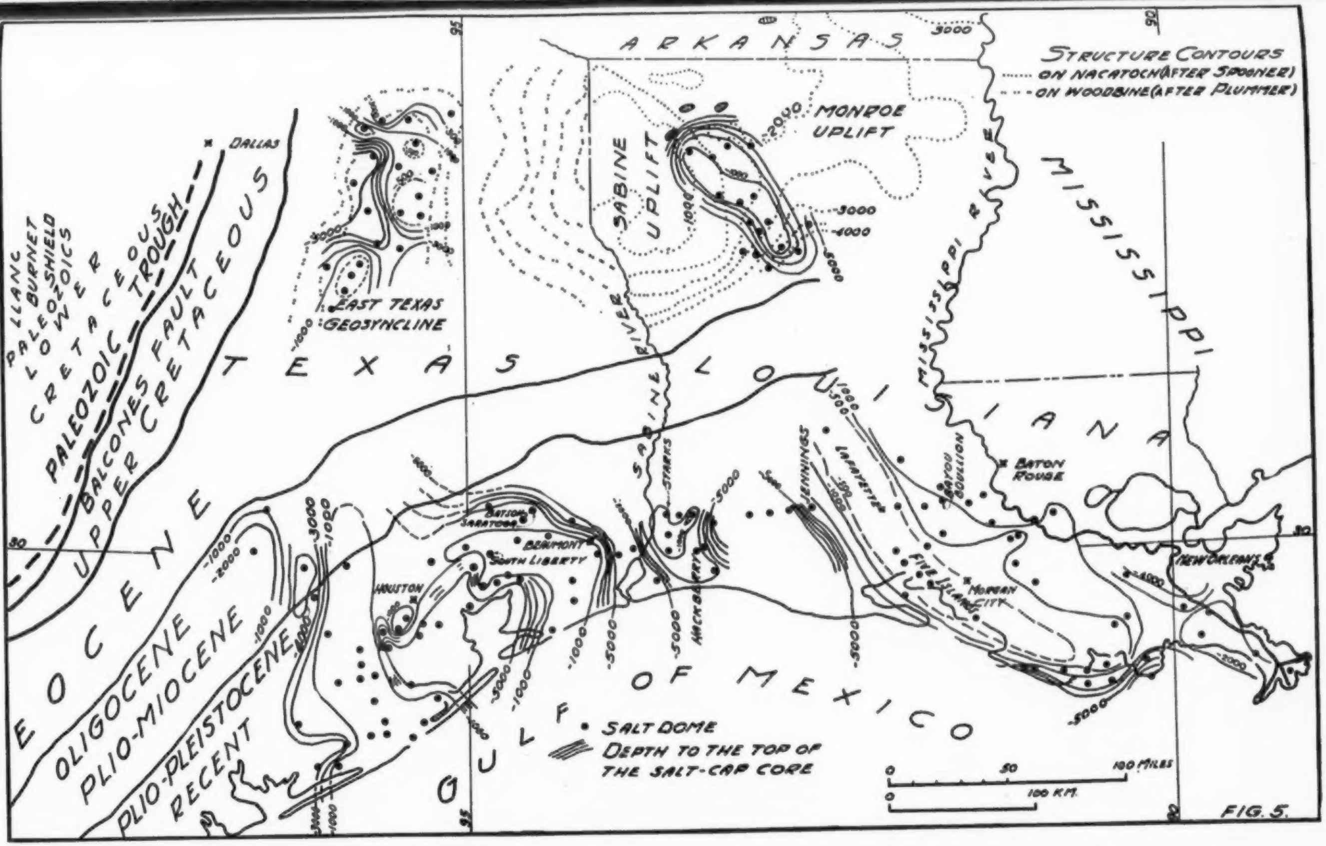

FIG. 5.—Sketch map of Gulf Coast area, showing salt domes, general geologic setting, and depth of salt-cap core below surface.

Apparent upthrust of the salt core in reference to the normal sediments will be produced by the compaction of the sediments above the mother salt bed, but no actual movement of the salt or salt core is produced by the compaction; and the only effect which the compaction exerts on the formation of the salt domes is slightly to increase the specific gravity of the sediments, correspondingly to increase the buoyancy of the salt, and thereby very slightly to accelerate the formation of the salt dome. The rate of compaction is considerable; and through the long period of time since the early Miocene, or since the Oligocene, or since the Jackson, the extent of the compaction should be considerable. Apparent uplift of the salt cores as the effect of the compaction should be taking place at present; if the length of the post-Pleistocene time is of the magnitude of 25,000 to 50,000 years, and if the actual rate of sinking of the surface as the effect of the compaction is approximately 50 feet per 100,000 years, mounds of 12–25 feet should be formed above the salt domes of the Gulf Coast; and, as a matter of fact, a great many of the shallow salt domes have mounds which do rise approximately 25 feet above their base. But if those mounds are to be attributed to the effects of compaction, it is difficult to see why other shallow salt domes, such as Big Creek, Boling, Hawkinsville, do not have mounds. A criterion between actual and apparent upthrust and doming of the surface is the fact that the apparent doming can not produce actual uplift of the surface beds above the level at which they were laid down; whereas, actual doming can produce such uplift. If Recent clays extend over the top of a mound of a Gulf Coast dome such as the Cote Blanche mound which rises 100 feet above sea-level, the doming must be actual and not apparent.

The magnitude of the theoretically probable subsidence of the upper beds under the effect of compaction is large enough so that account must be taken of it in calculations in regard to the real or apparent uplift of the salt cores; but compaction can have produced only a minor part of the relative uplift which we can observe.

ABSENCE OF DYNAMIC THRUST

Horizontal, compressive thrust can not have been the effective force which produced the Gulf Coast salt domes.

The latest and nearest overthrusting and compressive folding of considerable magnitude was that of the late Paleozoic age in the Ouachita Mountains of southeastern Oklahoma and of Arkansas and southwestward in front of the present Llano-Burnet uplift to the San Antonio area (Fig. 6). The not very intensely folded anticlines of the

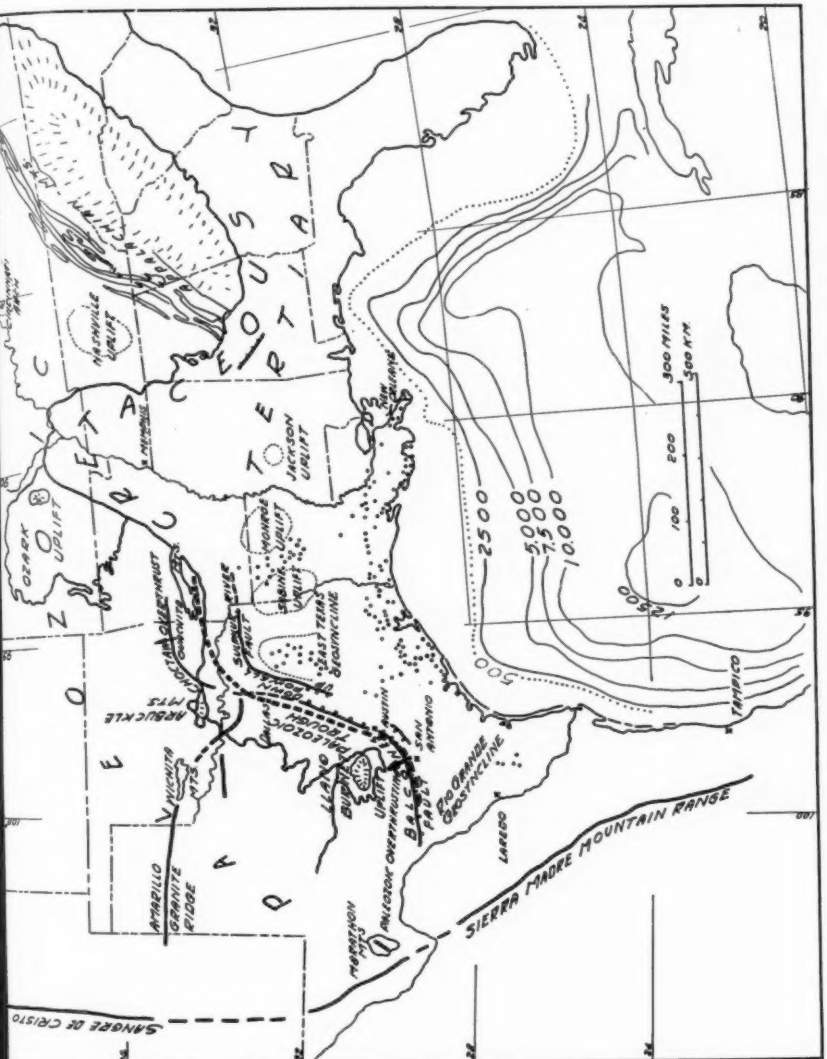

FIG. 6.—Sketch map showing general geologic setting of occurrence of Texas-Louisiana salt domes.

Sabine uplift have been interpreted as indicating possible gentle horizontal compression of Cretaceous beds in northern Louisiana. The Cretaceous beds of eastern Texas, central Texas, and southwest Texas are cut by many normal faults but show no evidence of horizontal compressive folding or of overthrusting. The Tertiary beds of the Gulf Coastal Plain of Texas and Louisiana are cut by tension faults and are domed and warped vertically but do not show horizontal compressive folding or overthrusting. The salt cores of the domes are circular or only slightly elliptical as far as they are known from drilling data; the salt-dome mounds, which are the imprint of the form of the top of the salt core upon the surface, are circular; the gravity minimum which is characteristic of the Gulf Coast salt domes is the effect of the roots of the dome; the minima of the known domes characteristically are circular or very faintly elliptical; the circular form of those minima indicates that these salt cores are circular or sub-circular in plan to very great depth and that these salt cores do not rise out of salt anticlines at great depth. The form of the salt domes, therefore, indicates the absence of horizontal compressive thrust in the Gulf Coast. Slight elongation is shown by many of the Gulf Coast domes, but presumably indicates the trend of the zone of weakness in which the salt dome formed.

It seems doubtful, therefore, whether horizontal dynamic thrust can have any considerable effect in the formation of the salt domes in the Gulf Coast during the post-Cretaceous and the Upper Cretaceous time.

STATIC THRUST OF SEDIMENTS

The static downward thrust of the weight of the sediments, and the buoyancy of the salt in reference to the sediments must provide the effective force in the formation of the Gulf Coast salt domes during post-Cretaceous time and presumably also during Upper Cretaceous time. That force presumably has not upthrust the salt domes from the present level of the mother salt bed to their present position. Part of the upthrust is real; but part is apparent; and much of the formation of the domes must have been by downbuilding of the base of the domes.

ACTUAL UPTHRUST PRESENT

Actual, and not merely apparent, upthrust of the salt cores must have taken place in the Gulf Coast. The salt of the mother salt bed will become plastic only after subsidence, concomitant sedimentation, and the consequent burial of the mother salt bed have raised the temperature and pressure above the critical point; salt domes can

begin to form only at or below the depth at which that critical point is reached. Salt domes which form by downbuilding can never rise above the level of that depth in earth space, unless they be lifted above it by epeirogenic uplift. Having been lifted above that critical level, they may be able to hold their position in earth space, but as long as they form only by downbuilding, their crest can be raised yet higher in earth space only by further epeirogenic uplift. Many of the shallow salt domes rise to the surface or very near to the surface and rise far above whatever that critical level is in the Gulf Coast. There has presumably been slight epeirogenic uplift at several times in the Tertiary; but the total must have been small compared with the upthrust necessary to raise the salt core of the many shallow domes in the Gulf Coast from that critical level to its present position. Those salt cores must have undergone some actual, and not merely apparent, upthrust.

Actual, relatively recent upthrust must have produced the doming of the surface to form the mounds at Belle Isle, Cote Blanche, and at the others of the Five Islands in Louisiana, and at Davis Hill in Texas. All of these mounds rise at least 80 feet above their base and above sea-level; Davis Hill rises 200 feet above the general level of the highest (early Recent or late Pleistocene) terrace of Trinity River and approximately 275 feet above sea-level. Furthermore, if the doming of the surface had been produced by subsidence of the sediments around a salt core stationary in earth space, according to the downbuilding theory of salt-dome formation: (1) all the domes which rise to equal depth below the surface should show approximately equal doming of the surface; and (2) the general level of the surface in the area would have to have sunk to an extent equal to the apparent doming of the surface. But, as a matter of fact, some shallow domes have no surface mounds; others have faint, indistinct mounds; and others have mounds 20–30 feet high, and a few have mounds 100± feet high. Late Pleistocene to Recent sediments are present on the tops of the mounds of the Five Islands. It would seem very doubtful whether anyone would wish to postulate that the general surface level in that area has sunk more than 100 feet within Recent time. The doming of the surface to form the surface mounds on the Five Islands domes, Davis Hill, Barbers Hill, Damon Mound, must be ascribed to actual upthrust of the salt core.

DOWNBUILDING

Downbuilding of the root of the salt domes must have produced part of the formation of the domes in the Gulf Coast. The argument is as follows.

Subsidence of mother salt bed.—The mother salt bed of the Gulf Coast domes must have been sinking in earth space rather continuously for a very long geologic time. As deep as the drill has penetrated in the Gulf Coast, the beds which are encountered seem to have been deposited near the shore line rather than far at sea in great oceanic deeps. The beds, as a whole, tend to contain a greater number and greater thickness of marine intercalations progressively toward the coast, and to become progressively more non-marine toward the interior. At some stratigraphic horizons, the marine facies extends much farther inland than at others. But those shallow-water deposits of Pliocene, Miocene, Oligocene, and late Eocene age now lie buried at great depth. The base of the Miocene in the Houston area lies normally at a depth of 4,000 feet; and in the Morgan City area in Louisiana, the top of the Miocene lies at a depth of approximately 6,000 feet. Concomitant subsidence and sedimentation have been the general rule in the Gulf Coast as far back in the geologic past as the data are available. Part, probably a small part, of that subsidence may have been produced by flowage of the sedimentary prism toward the unsupported edge of the continental shelf and by the consequent horizontal stretching and vertical thinning of the prism of sediments. Another small part of the subsidence in the upper beds will have been produced by the progressive compaction of the lower beds. But the largest part of that subsidence of the upper beds presumably must be attributed to the subsidence of the basement. It is necessary to postulate generally continuous subsidence of the mother salt bed at least throughout the Tertiary and Quaternary, and probably also in the late Cretaceous.

Depth of domes in past.—The crest of the salt-cap core of many Gulf Coast salt domes has been about as near or nearer the surface at times in the geologic past than it is at present.[13] The evidences of that former, as well as the present, shallowness of those domes are as follows.

1. Angular unconformities are present in the flank sediments of many domes; similar deformation at or near the surface in general is found only on domes on which the salt-cap core comes within a shallow depth below the surface; those old domes presumably were shallow domes at the time of the formation of those unconformities.

2. The beds which rest on the top of the salt-cap core on some domes are Pleistocene; on other domes, Pliocene, Miocene, Oligocene, or Jackson (Eocene) beds which have not been uplifted greatly and

[13] Marcus Hanna adduces evidence to much the same effect in a paper which is to appear in the Association's volume, *Structure of Typical American Oil Fields*, Vol. 3.

which lie unconformably on the cap-salt core; the crest of the cap-salt core must have been at the surface just before the deposition of those unconformably overlying beds; on other domes, a thin section of yet older beds is intercalated unconformably beneath those beds and above the salt or cap the crest of the salt-cap core of those domes must have been within a shallow depth below the surface at the time of the deposition of those unconformably overlying beds.

3. The upper part of the cap, particularly the lime rock[14] which forms the upper part of the cap rock of many domes, shows the effects of much solution. There is a complex question: (1) whether the solution took place at the time of the alteration of the anhydrite-gypsum cap rock to the lime rock, (2) what caused that alteration,whether that alteration could, or must, have taken place well below the surface, (3) whether the solution wholly or in large part has been subsequent to the formation of the lime rock, or (4) whether such solution could have taken place at considerable depth below the surface, or whether it is necessary to postulate shallow depth or exposure at the surface for the cap rock at the time of the solution.

4. If a present-day shallow dome has been upthrust from great depth to its present position, the relatively flat-topped salt-cap core must have punched its way through a great thickness of sediments; part of the necessary displacement of sediments might be effected by lateral side-tracking and compaction, but much of the displacement should be produced by the upthrust of a prism of sediments ahead of the salt-cap core; a thin prism of very greatly uplifted sediments is found on some of the deeper shallow domes, but in general, such an upthrust prism of sediments is not present on the shallow domes, or, if present, is so thin as not to be recognized in the wells; definite proof, of course, is impossible that on a particular dome, a thick prism was not uplifted and later eroded immediately before the deposition of the beds, which now lie unconformably upon the salt-cap core; the absence of the prism of uplifted sediments might be produced equally well by the non-deposition or greatly reduced deposition of sediments over a shallow salt dome plus the rapid alternation of periods of deposition and of the erosion of a subsequently formed salt-dome mound. But in any of those cases, the crest of the dome must have been shallow.

It therefore seems probable that the shallow domes of the present day have been shallow domes for a long time.

Growth by downbuilding.—Much downbuilding of the base of the

[14] The term "lime rock" is used to obviate the objection to the use of the term "limestone," for a rock which is not of sedimentary origin.

salt core in earth space presumably, therefore, must have taken place. We can not prove definitely that the formation of the domes has not been periodic, that the salt core has not subsided for a time with the subsidence of the mother salt bed and that later it has been uplifted in earth space back into its former level in earth space, but it seems more probable that formation of the Gulf Coast domes has been more or less continuous; and if it has been continuous, the growth of the salt core and of the dome as a whole must have been largely by downbuilding, for if the crest stays approximately constant in earth space, growth can be only by downbuilding in earth space.

Energy available.—The small quantity of the energy which is available would seem to indicate that the formation of the Gulf Coast salt domes has been produced largely by downbuilding.

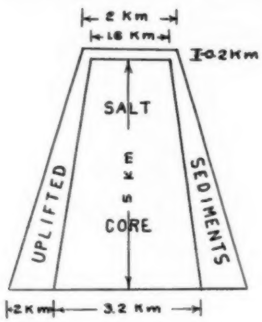

FIG. 7.—Vertical dimension diagram of salt dome.

Structurally, the difference between growth of the domes by downbuilding and by upthrust is slight; the salt moves inward from the mother salt bed and the salt core moves stratigraphically upward in essentially the same way under downbuilding as under upthrust. But dynamically, there is a great deal of difference between growth of a dome by downbuilding and by upthrust. The energy requirements for growth by upthrust are much greater than for growth by downbuilding.

Calculations of available energy for ideal average salt dome.—The following is a calculation of the approximate magnitude of the energy available.

A Gulf Coast salt dome of average size with flaring flanks is assumed to have the dimensions of the dome in Figure 7.

1. The buoyant upward pressure of the salt core, by itself, will equal the relative deficiency in weight of a vertical prism of the salt of

unit cross section: $=5\times10^5\times1\times1\times0.12=6\times10^4$ grams = 60 kilograms per square centimeter = 850 pounds per square inch; where 0.12 is the mean deficiency of specific gravity of the salt in reference to the sediments, and where $5\times10^5=5$ km. in cm. = the vertical dimension of the salt core; and 1×1 = the horizontal area of the prism.

2. The buoyant upward pressure of the salt dome as a whole will be the sum of the effects of the salt core plus the effects of the uplifted sediments plus the effect of the cap rock.

The volume of the salt of the core in cubic centimeters =

$$5\times10^5\times\pi\times\left(\frac{1}{2}\times\frac{1.6+3.2}{2}\times10^5\right)^2 = 22.5\times10^{15}\text{ cc.}$$

The deficiency of weight of the salt of the core then will be: $0.12\times22.5\times10^{15}\times2.75\times10^{15}$ grams.

The volume of the aureole of uplifted sediments then will be:

$$5.2\times10^5\times\pi\times\frac{1}{4}\left(\frac{2+7.2}{2}\times10^5\right)^2 - 22.5\times10^{15}=64\times10^{15}\text{ cc.}$$

The excess of weight of the aureole of uplifted sediments then will be: $0.03\times64\times10^{15}=+1.93\times10^{15}$, where the mean specific gravity of the aureole of uplifted sediments is 0.03 greater than that of the normal sediments.

If an average cap of anhydrite about 100 meters thick is present, the volume of the cap will be:

$1\times10^4\times\pi\times\frac{1}{4}(1.6\times10^5)^2=0.2\times10^{15}$ cc.

The excess of weight of the cap will be: $0.7\times0.2\times10^{15}=0.14\times10^{15}$ grams where the specific gravity of the anhydrite is 0.7 greater than that of the normal sediments.

The total excess or deficiency of weight of the salt dome taken as a composite of the salt core plus the aureole of uplifted sediments plus the cap will be: $-2.75+1.93+0.14=-0.68\times10^{15}$ grams.

The mean diameter of the salt dome (salt core + aureole of uplifted sediments) may be taken as approximately 5 kilometers; and the mean horizontal cross section will be: 196×10^{10} square centimeters.

The pressure per square centimeter then will be:

$$\frac{-0.68\times10^{15}}{19.6\times10^{10}}=3.5\times10^3$$ grams per square centimeter, $=-50$ pounds per square inch.

If we take one of the large domes, the diameter of the salt core may be assumed to be twice that of an average dome; the volume of the salt of the core will be four times that of the average dome; the width of the aureole of uplifted sediments may be assumed to be the same as that of a dome of average size; and the volume of the aureole of uplifted sediments will be twice that on the dome of average size.

The deficiency in weight of the salt of the core will be: $-2.75\times10^{15}\times4=-11\times10^{15}$ grams.

The excess of weight of the aureole of uplifted sediments will be: $+1.93\times10^{15}\times2=+3.9\times10^{15}$ grams.

The excess of weight of the cap will be: $0.14\times10^{15}\times4=0.6\times10^{15}$ grams.

The total deficiency in the weight of the salt dome will be: $(-11.0+3.9+0.6)\times10^{15}=6.5\times10^{15}$ grams.

The mean diameter of the dome may be assumed to be 7 kilometers and the mean area of cross section of the dome will be 39×10^{10} square centimeters.

The pressure will be:

$\frac{-6.5\times10^{15}}{39\times10^{10}}=-1.7\times10^{4}$ grams $=17$ kilograms $=-235$ pounds per square inch.

The buoyant pressure on the domes in which the flank of the salt core is nearly vertical must be much less than those calculated pressures for the domes with flaring flanks. The torsion balance indicates that the salt core of such a shallow dome as Fannett does not flare with increasing depth.

The volume of the salt in the lower part of the dome will be less than in a flaring dome; and the buoyancy of the salt will be correspondingly less. The uplift of the flank sediments should be less than on a flaring dome; and the negative buoyancy of the aureole of uplifted sediments should be less than on a dome which has a flaring salt core.

Calculation of available energy from gravity anomalies.—The gravity anomaly which is produced by a salt dome is a measure of its buoyancy. The amplitude of the gravity anomalies of the Gulf Coast salt domes in general ranges from -9.0 to -0.3 milledynes, if the superficial maximum effect of some domes is disregarded; most commonly the amplitude is approximately 30 milledynes.

The magnitude of what the writer assumes to be a standard flaring dome of average size is 3.0 milledynes. Fannett probably has an anomaly of approximately 1.0 milledyne from the evidence of the scanty torsion-balance data which are available to the writer. The center of gravity of the Gulf Coast domes of the Houston district may be assumed to be at a depth of approximately 3 kilometers. According to Newton's law of attraction, the following equation holds.

$$\text{Attraction}=\frac{\text{gravity constant}\times\text{deficiency of mass}}{\text{square of distance}}$$

$$= 3.0 \times 10^{-3} = \frac{67 \times 10^{-9} \times \text{deficiency of mass}}{(3 \times 10^5)^2}\text{; and}$$

Deficiency of mass $= 4.0(+) \times 10^{15}$ grams.

The range in the deficiency of mass, therefore, will be from 12×10^{15} to 1.0×10^{15} grams.

The mean areal cross section of the domes will probably range from 20 square miles (50 square kilometers) to 7 square miles (20 square kilometers) and the buoyant upward pressures will range from 24 kilograms per square centimeter or 350 pounds per square inch, to 4 kilograms per square centimeter or 60 pounds per square inch. If the center of gravity is at a depth of 4,000 meters, the figures would be 50 kilograms per square centimeter or 700 pounds per square inch to 8 kilograms per square centimeter or 115 pounds per square foot. Those figures are only crudely approximate; the actual formula for the attractive effect of the salt dome is much more complicated; and the mass of the salt dome may not be assumed to be concentrated at the center of gravity. The figures, however, give a corroboratory estimate of the approximate magnitude of the buoyancy of the salt domes.

Those buoyant pressures are rather small. A pressure of 1 kilogram per square centimeter is equal to the pressure of 33 vertical feet of water and a pressure of 20 kilograms per square centimeter is equal to the pressure of 667 vertical feet of water.

That buoyant upward pressure is a measure of the available excess of energy above that which is necessary to overcome gravity in the work of uplifting the salt dome in earth space. It is energy which is available for the overcoming of internal friction within the salt in its flowage from the mother salt bed into the root of the dome, and in the flowage within the salt core; for the overcoming of the external friction between the salt core and the surrounding sediments; for the overcoming of friction within the sediments which are being deformed; for punching a way for the salt core through the overlying sediments; and for overcoming the inertia of the mass of the salt dome.

Energy available under upthrust versus that under downbuilding.—The salt dome and the surrounding sediments may be regarded as a system which is composed of two prisms which are so connected that the one must move upward as the other moves downward. The system may be represented by the two prisms, *A* and *B*, in a weightless tube immersed in water; prism *A* will represent the salt dome and prism *B*, the normal sediments (Fig. 8).

If *A* and *B* are perfectly balanced and if there is no friction in the system, no work will have to be done against gravity to raise *A* and to drop *B* equally, for the energy acquired by the downward movement

of *B* with gravity will equal the work necessary to raise *A* against gravity.

If *B* is slightly heavier than *A* and if friction tends to retard movement of *A* and *B*, *A* will tend to rise and *B* to sink equally; and part of the weight of *B* may be regarded as perfectly counterbalancing the weight of *A*; and again no work will be done against gravity in raising *A* and dropping that part of *B* equally; and the rest of the weight of *B* will not be counterbalanced by any part of *A*. Downward movement of that excess of weight of *B* over *A* will develop energy which will be available to overcome the frictional resistance to movement of *A* and *B*.

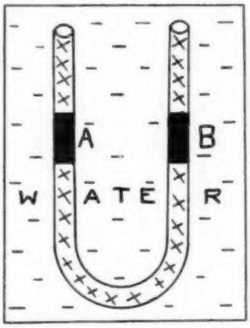

FIG. 8.—Diagrammatic sketch to illustrate energy requirements of system of uplifted salt core plus normal sediments.

If *A* remains fixed in earth space while *B* and its leg of the *U* tube is dropped an equal distance, the downward movement of the excess of weight of *B* over *A* will develop the same energy which it would develop if *A* had risen equivalently to *B*'s drop; but the downward movement of that part of *B* which is counterbalanced by *A* will develop energy which will not be expended in work in raising *A* against gravity, and which will be available to overcome frictional resistance to the movement of *A* and *B*.

The ratio of that part of *B* which is counterbalanced by *A*, plus the excess of *B* over *A*, to the excess of *B* over *A* is approximately 100:5 for the Gulf Coast area. The ratio of the energy which will be developed by the downward movement of the whole of *B* to that developed by the excess of *B* over *A* necessarily will be the same, 100:5.

The energy which is available for the overcoming of friction and for any work other than the uplift of the salt core against gravity,

therefore, will be approximately twenty times greater in the Gulf Coast if the dome grows wholly by downbuilding than if it grows wholly by upthrust.

Predominance of downbuilding.—Downbuilding, therefore, must have produced a large part of the formation of the Gulf Coast salt domes. It is impossible to estimate even the approximate magnitude of the friction which is involved in the formation of a salt dome. But the friction between the sediments and the irregular surface of a salt core 6,000 meters high by 2,000 to 4,000 meters in diameter must be very great; and in addition there is internal friction within the salt, and within the sediments which are deformed. The energy which is available to overcome that friction seems from the preceding calculations to be much too small, if the Gulf Coast domes grow only by upthrust. The available energy will be approximately twenty times greater, if the domes grow only by downbuilding. Subsidence of the mother salt bed has been taking place nearly continuously through the known period of formation of the Gulf Coast salt domes. Much of the growth of the domes presumably, therefore, must have been by downbuilding.

Corroboratory evidence from Clay Creek.—Partially corroboratory evidence of the growth of the Gulf Coast salt domes by downbuilding is given by the coincidence of the cessation of relative upthrust of the Clay Creek dome with the cessation of regional subsidence. Throughout the Eocene there was, in general, progressive subsidence and concomitant sedimentation in the Clay Creek area; the Eocene section is at least 5,500 feet thick, and in large part, the sediments are marine; the surface must have been not far from sea-level throughout the Eocene; and sedimentation must have been compensated by, or must have compensated, equivalent subsidence. The Eocene section is overlain only by the Catahoula (Oligocene? basal Miocene?) and the Oakville (Miocene). Both formations are non-marine in that area. The base of the Catahoula normally should lie at an elevation of +50 feet at Clay Creek. The subsidence which had prevailed through most of Eocene time, must have stopped by the beginning of Catahoula time, or it may have persisted for a short while into Catahoula time at a lesser rate than the sedimentation and then have been followed by slight uplift. If downbuilding has been the dominant factor in the formation of Gulf Coast salt domes, the growth and relative uplift of the Clay Creek dome theoretically should cease at the end of the Eocene or between the end of the Eocene and some time early in the Catahoula period. The numerous key beds give a clear record of persistent relative upthrust of the Clay Creek dome through Wilcox

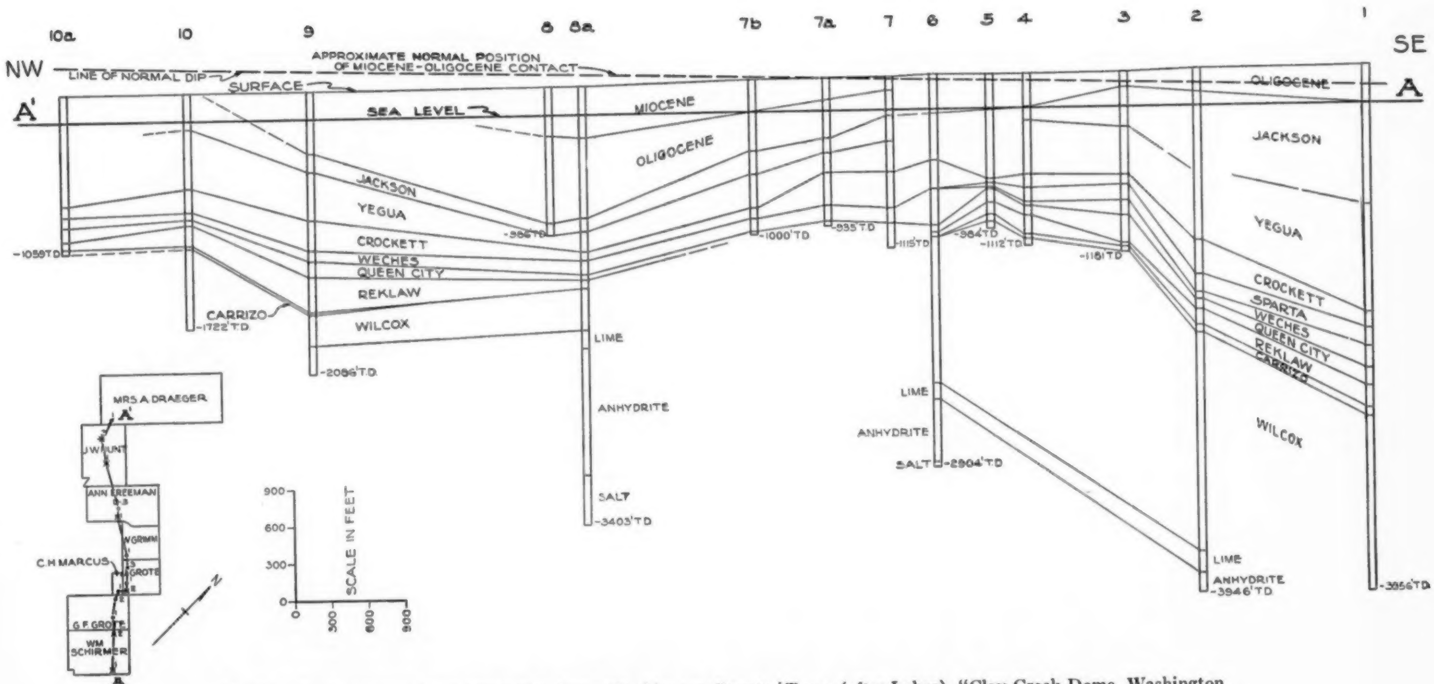

Fig. 9.—Section across Clay Creek salt dome, Washington County, Texas (after Lahee), "Clay Creek Dome, Washington County, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 3 (March, 1931), p. 280, Fig. 1

(early Eocene) to Jackson (latest Eocene) time. The Wilcox formation, which rests unconformably on the cap, and all the later Eocene formations, become thinner from the outer flank to the crest of the dome. That thinning indicates continued relative upthrust during the period of deposition of those formations. But the overlying Catahoula and Oakville thicken from the outer flank to the center of the dome. That thickening of those overlying formations indicates the cessation of movement of relative upthrust of the crest of the salt core, and in fact indicates replacement of the upward movement by downward movement of the top of the salt. We can not prove that in post-Eocene times, upthrust of the salt has not been overbalanced by solution of the crest of the salt core. But it looks strongly as if all considerable movement of upthrust had ceased by early Catahoula time. Growth of the Clay Creek dome, therefore, stopped at the time when, theoretically, it should have stopped if the dome were growing wholly by downbuilding. Cessation of the growth of a salt dome can be the result of any one of several but not many factors. The coincidence of the cessation of growth of the Clay Creek dome with the cessation of the regional subsidence in that general area, is suggestive evidence, but not conclusive proof, of the growth of the Clay Creek dome predominantly by downbuilding.

Greater upthrust of larger domes.—Actual upthrust of the salt core theoretically should be slightly easier in a dome of large diameter than in a dome of small diameter. The external friction between the salt and the sediments should be less per unit volume of salt in a dome of large diameter than in a dome of small diameter; and at the same time, the buoyant upward pressure should be greater. There is partial, but not conclusive, evidence of a tendency for greater uplift on the larger Gulf Coast salt domes than on the smaller. The evidence comes from the height of the salt-dome mounds and from the depth of the top of the salt-cap core.

TABLE I

HEIGHT OF MOUND VERSUS SIZE OF DOME*

Height of mound in feet		*200*	*100±*	*50±*	*5 to 30*	*0*
Size of dome	*Diameter of dome in miles*					
Very large	2½	—	—	—	2†	4†
Large	2±	1	4	3	1	0
Average	1±	—	—	1	13	15
Small	0.8	—	—	—	1	3
Pearson correlation coëfficient					0.46±0.11	

* Domes in the Louisiana Coastal swamps and bays and in the Mississippi River bottoms are excluded. Deep domes excluded.

† One dome in erosion area.

The surface mounds of the salt domes of larger diameter tend to be higher than those of the salt domes of smaller diameter. The relation of the height of the mound to the size of the dome is given in Table I. The Pearson correlation coëfficient between the largeness of the dome and the height of the mound is 0.44, with a probable error of ±0.11. The probable error is rather large; the correlation is not certain, but there are more than 99 chances out of 100 for some degree of correlation to less than 1 chance out of 100 of no correlation. But it seemingly must be more than an accident that no average or small-sized dome has a mound more than 50 feet high, although five large domes have mounds more than 50 feet high, and three large domes have mounds approximately 50 feet high.

The depth to the top of the salt-cap core of the Gulf Coast salt domes tends to be less for the domes of large diameter than for those of small diameter. The variation of the depth to the top of the salt-cap core with different sized domes is given in Table II. Statistically, the degree of correlation between the depth and size of the domes is poor. If the crude data are used, the Pearson correlation coëfficient is 0.21, and its probable error is ±0.08. But the variation of depth with size seems to be complicated by a normal decrease in the frequency of domes with increasing depth. The tendency is well shown by the domes of average size, and less clearly by the large domes. If the deviation in number of domes from the normal frequency at each respective depth is used instead of the crude number of domes, the Pearson coëfficient for correlation between depth and size of the dome is increased to 0.37 with a probable error of ±0.10; statistically, therefore, there would be approximately 99 chances out of 100 of some degree of correlation and 1 chance of no correlation. The depth of the medium large and very large dome is 550 feet; and of the medium small and very small dome, 950 feet. Fifty percent of the large and very large domes rise above a depth of 550 feet; only 22 percent of the average-sized and small domes rise above a depth of 550 feet. Some correlation between the size of the dome and the depth to the top of the salt-cap core would, therefore, seem probable.

Slightly greater upthrust of the domes of large diameter than those of small diameter, or at least a tendency toward such a greater upthrust of the larger domes, seems to be suggested strongly, although it has not been proved beyond a shadow of a doubt. The greater upthrust of the larger domes might be caused by the lesser friction of the salt core with the sediments, or by the slightly greater buoyant upthrust of a large dome than of a small one, or more probably, by a combination of the two factors.

TABLE II

DEPTH OF SALT OR CAP VERSUS SIZE OF DOME

Depth of salt	+*100*	*0 to −250*	*−250 to −500*	*−500 to −750*	*−750 to −1,000*	*−1,000 to −1,250*	*−1,250 to −1,500*	*−1,500 to −1,750*	*−1,750 to −2,000*	*−2,000 to −3,000*	*−3,000 to −4,000*	*−4,000 to —*	*Total*
Size of dome													
Very large	—	1	1	—	1	1	—	—	—	—	1	—	5
Large	1	5	2	1	1	2	1	—	—	2	—	—	15
Average	—	3	6	8	7	3	5	2	2	4	4	2	46
Small	—	1	1	—	1	—	—	1	—	—	1	1	5
Smoothed normal occurrence	1.4	14	15	12.6	11.2	9.8	8.4	7.0	5.5	7.0	5.5	2.7	=100

Large and very large domes in which top of salt or cap rises above depth of 350 feet below general level of surface	10
Percentage of whole number of large and very large domes	50
Average and small domes in which top of salt or cap rises above depth of 550 feet below gencral level of surface	11
Percentage of whole number of average and small domes	22
Depth of median very large and large domes	550 feet
Depth of median average and small domes	950 feet
Pearson correlation coëfficient for increasing depth with decreasing size	0.21 ± 0.08
Pearson correlation coëfficient—after correction has been made for normal decrease in number of domes with depth	0.37 ± 0.10

Upthrust of cap.—The enigma of the ability of the cap to maintain its seemingly precarious perch on the top of the salt core largely disappears under the theory of downbuilding of the domes. The cap at Sulphur, Louisiana, is approximately 1,000 feet thick vertically and is perched on a base approximately 1,500 feet in diameter. The cap of most domes is thinner and rests on a wider base. It is difficult to see how the salt could have maintained its position during dynamic upthrust through 15,000–20,000 feet of sediments. But if the cap has merely rested on top of the salt core under no very great cover of sediments, while the sediments settled quietly past it, there is no particular reason why the cap should be toppled from its perch. The cap rock of many domes, however, does show evidence of shearing under considerable vertical pressure; but no quantitative estimate has been made of the depth necessary to produce such shearing. The shallow domes presumably must have been upthrust several thousand feet; and thick cap rock is found on very many shallow domes. The cap, therefore, must have been upthrust several thousand feet, although it probably has not been upthrust 15,000–20,000 feet.

CESSATION OF GROWTH OF GULF COAST DOMES

Only a few domes have had appreciable growth within very recent geologic time. Cessation of growth of the other domes has come at different times.

The Recent uplift on such domes as the Five Islands, Barbers Hill, and Davis Hill has been described in a previous paragraph. Reliable instrumental evidence of uplift within humanly recent time is not available; but geologically, growth would seem probably still to be going on.

Many domes show much growth as late as some time in the Pleistocene, but essentially no growth in the post-Pleistocene; the surface of the Beaumont (late Pleistocene) prairies is domed less than 5 feet over such shallow domes as Big Creek, Boling, Hockley, and Hawkinsville. That doming is explainable by the effects of the compaction of the sediments. Cessation of growth on those domes must have come late in the Pleistocene.

Many domes show active growth through the Pliocene and very little growth during Pleistocene and post-Pleistocene times. At Bryan Heights, 750 feet of Pleistocene and Plio-Pleistocene sands and gumboes extend across above the cap-salt core. The thick basal gumbo bed, which rests on the cap, shows contemporaneous uplift during the deposition or else erosion immediately after its deposition. The lower overlying beds are domed faintly. There is a 30-foot surface

mound. Thirty feet of uplift, less perhaps 5 feet of apparent uplift from compaction, therefore has taken place since the Pleistocene. But the top of the cap must have been at or near the surface immediately before the deposition of that basal Plio-Pleistocene gumbo; and now the top of the cap lies at a depth of 750 feet. Cessation of the main growth movement must have begun by the beginning of the Pleistocene; and since that time, the dome has been sinking in earth space with the general subsidence of the Gulf Coast.

Many domes show active growth through the Oligocene, little growth in the Miocene, and no growth in the post-Miocene. At such a dome as Sugarland, the Oligocene is reported to be much domed, and the Fleming (Plio-Miocene) to be only slightly domed. The cap is immediately overlain by Oligocene beds and, therefore, must have been at the surface early in Oligocene time, although now it lies at a depth of 3,400 feet. Cessation of the main growth movement must have come by the late Miocene; and since that time, the dome must have sunk with the sediments in the general subsidence.

The cessation of growth of the Clay Creek dome at the end of the Eocene has been discussed in a previous paragraph.

The presence of many very deep domes is being indicated by the results of torsion-balance surveys. Reflection seismic surveys of some of those prospective domes indicate uplift of only a few hundred feet at depths of 6,000, 7,000, or 8,000 feet. Cessation of growth on those domes must have come by the end of the Eocene.

Final cessation of growth of the Gulf Coast salt domes seems to have had no temporal plan. The growth of some domes stopped far back in the geologic past; some domes seem still to be growing; others have stopped growing at various times in the geologic past. There is, however, a suggestion of an areal plan. In the areas of shallow domes (Fig. 5), growth has persisted to the present or until very late in the geologic past. But in the areas of very deep domes, growth ceased far back in the geologic past.

Causes of cessation of growth.—The causes of such final cessation of the growth of salt domes may be several: (1) exhaustion of the salt in the mother salt bed; (2) attainment of isostatic equilibrium; (3) frictional freezing of the salt core to the sediments; and (4) in the case of growth by downbuilding, cessation of the regional subsidence.

Exhaustion of the salt may stop the growth of the dome or may merely retard it. If the deeply buried sediments behaved as a true liquid, the effective transmission of the static downward thrust of the sediments as an upward thrust on the salt core would be the same, whether or not the base of the salt core were attached to a horizontal

mother salt bed. But as the deep sediments should not behave as a true liquid, their static thrust should be transmitted more effectually to the salt core through the horizontal mother salt bed than directly to the steep side of the salt core. Exhaustion of the salt of the mother salt bed, therefore, should reduce the effective buoyant force of upthrust; and, if that reduced force of upthrust be insufficient to overcome the frictional resistance to upthrust, the salt core would be frozen by friction to the sediments; and growth of the dome would cease.

The attainment of isostatic equilibrium means that the downward thrust of the prism of the salt dome equals the downward thrust of the sediments. The buoyant force of upthrust, which is the difference between the two thrusts, becomes zero. Growth of the dome must then cease except for slight upthrust to compensate loss of salt by solution and for the slight upthrust of the salt plus the aureole of uplifted sediments.

Frictional freezing of the salt core to the sediments ultimately may cause the final cessation of growth in a dome. The friction per volume of sediments increases with decrease in the diameter of the salt core. In the old age of a salt dome, the diameter of the salt core tends to decrease as its vertical dimension increases. The frictional resistance to movement of the salt core relatively to the sediments should increase correspondingly and ultimately may freeze the salt core to the sediments. The growth of the dome will cease finally when the system salt plus uplifted sediments attains isostatic equilibrium, and thereafter the dome will sink, stand still, or rise with the surrounding sediments.

Growth of a dome by downbuilding can take place only as long as general subsidence of the area takes place; and as soon as the subsidence stops, growth of the domes by downbuilding must stop.

Downward relative movement.—Retrograde movement possibly is shown by a few domes. A central syncline is present in the sediments above the salt and cap on the Clay Creek dome, Washington County, and on the Boggy Creek dome, Anderson County, Texas. A central depression at the surface is present over the Vinton dome, Calcasieu Parish, Louisiana, Jefferson Island dome, Iberia Parish, Louisiana, Belle Isle dome, St. Mary Parish, Louisiana, and Orchard dome, Fort Bend County, Texas. A thick cap overlies the salt on the Vinton dome; a moderately thick cap overlies the salt under the depression on the Belle Isle dome, and a moderately thick cap overlies the salt over much of the area of Lake Peigneur, which is the central depression of the Jefferson Island dome. Both Clay Creek and Boggy Creek

have a very thick cap. Simple solution of an unprotected salt spine can not have been the cause of the depression of the crest of the salt on those domes. On Jefferson Island, there is a subsidiary spine of salt; and on Belle Isle, at least, two subsidiary spines of salt, which rise nearly to the surface beside the central depression, whose uplift produced the present surface mounds, and in connection with which there is no evidence of depression. The central depression on those two domes might be attributed to transference of the salt from the center of the dome, perhaps as an effect of the weight of the cap, into the spine or spines. At Clay Creek, the numerous key beds give a clear record of persisting relative upthrust of the dome through the Jackson (latest Eocene) and of the subsequent subsidence of the crest of the dome. The formations from the Wilcox (early Eocene), which rests on the cap, through the Jackson, show thinning from the outer flank to the crest of the dome. But the overlying Oligocene and Miocene formations thicken toward the center of the dome. That thickening indicates that the movement of relative upthrust during the Eocene not only ceased but was reversed and replaced by downward movement of the crest in reference to the surrounding sediments.

That central subsidence on the Clay Creek dome may have been produced either by subsidence of the salt core in reference to the surrounding sediments or by recession of its crest. The subsidence on the Clay Creek dome is attributed by Goldman[15] and others to solution of the top of the salt core. The thickness of the cap is 1,200± feet; and the major and minor axes of the cap and of the upper part of the salt core are respectively 7,500± and 9,000± feet; all but the upper 140 feet of the cap is anhydrite; rather commonly on the gulf, the anhydrite Coast salt domes consist of a tight impervious rock with few open fissures. Any solution by circulating waters should be at a maximum on the flanks, where the salt is in contact with sands, should be small over the top of the dome under that massive cap, and should be less over the central area than toward the edge of the top. Solution by diffusion may be more important than solution by circulating water; it should take place perpendicularly to the surface of the salt and proportionally to the water-filled porosity of the formations in contact with the salt. Recession of the surface of salt under solution by diffusion should be much greater at an angular corner than in the center of a nearly flat surface. Recession of the surface of the salt core, therefore, should be greater at the edge which is formed by the inter-

[15] M. I. Goldman, "Bearing of Cap Rock on Subsidence on Clay Creek Salt Dome, Washington County, and Chestnut Dome, Natchitoches Parish, Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 9 (September, 1931), pp. 1105–13, with counter argument by F. H. Lahee, pp. 1113–16.

section of the salt table with the flank than over the central area of the salt table. The maximum subsidence of the sediments to fill the space which was occupied by the dissolved salt should be over the edge of the salt core rather than over the center of the dome, unless very improbable conditions prevail. The published sections across the Clay Creek dome show that the maximum subsidence is over the center of the dome. The rate of diffusion, furthermore, is extremely slow and is calculated by Fulda[16] on the basis of the following formula by Nernst:

$$M = D \times \frac{C_1 - C_2}{l} t_1$$

where:

M = Weight in grams

D = Coëfficient of diffusion 1.1 for salt

C = Concentration of salt in brine in grams per cubic centimeter

t = Time in days

l = Distance between C_1 and C_2 perpendicular to the surface

to be 6 centimeters per 1,000 years for the special case of the solution of a horizontal salt table which lies 100 meters below the surface and which is overlain only by a column of brine whose concentration ranges from 0 gram per cubic centimeter at the surface to 0.32 gram per cubic centimeter at the surface of the salt. If the mean depth to the salt table at the Clay Creek dome in post-Eocene time is assumed to have been 2,000 feet and if it similarly had been overlain only by a column of brine reaching to the surface, the rate of solution by that formula would be 1 centimeter per 1,000 years. Solution at that rate would take 30,000,000 years to produce the observed subsidence at Clay Creek. The rate of diffusion through the relatively tight anhydrite must be much slower, and through the overlying sediments still slower, than that through a simple column of brine. But, on the other hand, the flow of fresh water in the super-cap sands across the dome should slightly speed the rate of diffusion. Nevertheless, 100 trillion years would seem necessary for sufficient solution to produce the observed super-cap subsidence at Clay Creek. The length of post-Eocene time presumably is less than 0.1 of 100 million years. Solution by diffusion, therefore, is not the immediate cause of the subsidence at Clay Creek.

Although recognizing that the evidence is insufficient and inconclusive, the writer inclines tentatively toward the belief in subsidence of the salt core or subsidence in the salt core as the main cause of the subsidence which has produced the central syncline at Clay Creek and Boggy Creek.

[16] Ernst Fulda, "Salzauslaugung," *Jahrbuch des Helleschen Verbandes*, Bd. 4, Lief. 2 (1924), p. 376.

Explanation of retrograde, downward relative movement of the salt core, such as that which the writer surmises to have taken place at Clay Creek, is difficult. Three possible plausible explanations can be suggested.

1. The buoyancy of the salt may be reduced below some critical point by solution of the salt. If the salt dome is static, if all movement of the salt core relative to the sediments has stopped, if the salt core is frozen by friction to the sediments, and if the salt dome as a system (of salt plus aureole of uplifted sediments) is in isostatic equilibrium, solution of the salt from the sides and the top of the salt core might destroy the isostatic equilibrium and produce a negative buoyancy, which might produce a retrograde movement of the salt dome. It is rather reasonable to expect that the dome may have been in isostatic equilibrium at the beginning of the Catahoula time, for (1) the cap is very thick and is composed predominantly of anhydrite, which has a high specific gravity; (2) the dome has a considerable aureole of uplifted sediments; and (3) the top of the cap now lies at a depth of 2,000 feet, has sunk approximately 1,000 feet since the beginning of Catahoula time; and, therefore, the top of the dome must have been at a shallow depth below the early Catahoula surface. Growth of the dome stopped between the end of the Eocene and the beginning of the Catahoula. Post-Eocene solution of the salt should reduce the positive buoyancy of the salt core and might destroy the isostatic adjustment and produce a negative buoyancy which should tend to produce subsidence of the salt dome in reference to the general mass of the sediments of the area. The energy which would become available by the production of the negative buoyancy, however, would seem small compared to the task of effecting actual subsidence of the dome.

2. An alternative hypothesis, which is suggested by Lahee, postulates

> that possibly this central basin is the result of mechanical settling of the inner part of the plug, perhaps occasioned by a relief of compression which must have existed during its rise through, and relative to, the surrounding strata. Evidence of similar post-compression relief is almost invariably observed in the normal faulting which affects folded prisms of strata.

3. Another hypothesis postulates that the excess of weight of the thick cap should cause the underlying upper part of the salt core to bulge outward and to displace the unconsolidated surrounding sediments. The negative buoyancy which is produced by the thick cap of the Clay Creek dome will be compensated by 6,000–7,000 vertical feet of the salt core, and should become negligible at a depth of 5,000–6,000 feet below the base of the cap. The effective thickening of the

salt core, therefore, would occur in the zone which lies immediately below the cap and which is not more than 5,000 feet in its vertical dimension. A 350-foot radial thickening of the vertical cylinder of the salt core, 5,000 feet high, would produce the 1,000-foot subsidence of the crest of the salt-cap core. That 350-foot horizontal outward movement of the edge of the salt core would have to be taken up by (1) reduction of the porosity of the sediments; or (2) deformation of the sediments so that elongation of the vertical dimension would compensate the shortening of the radial horizontal dimension without essential change of volume of the sediments. The pressure from the excess of weight of the cap above the normal pressure of the overlying sediments is small; the plastic deformation of the sediments around the salt core without change of volume or the compression of these sediments by reduction of the pore space both involve the overcoming of much friction within the sediments as well as friction within the salt mass itself. The quantity of energy available for the task seems rather too small.

Similar central collapse above the salt core is present on some of the salt domes of the North German plain, and commonly is explained by German geologists as the result of solution.

Central collapse above the salt core impresses the writer as perhaps being a phenomenon of the old age of salt domes after they have become static. The post-Eocene uplift of the interior domes of Texas and Louisiana, to which groups Boggy Creek, Texas, and Chestnut, Natchitoches Parish, Louisiana, belong, presumably has been small. Clay Creek is the innermost of the Coastal group of domes; but like the interior domes it has had little uplift since the Eocene; it therefore might exhibit an old age characteristic which would not be present on the more lately active domes nearer the coast.

Solution of the salt must produce considerable effects in a dome which is static through long periods of geologic time. Solution can produce considerable effects in a short period of geologic time on a well exposed salt mass. A salt spine several hundred feet high on the Cote Blanche dome, for example, was dissolved during early Recent time; the unconsolidated surface marsh clays have a thickness of a few tens of feet over the area surrounding the dome, but thicken to a few hundred feet under the crest of the present mound. The Pleistocene sands and gravels do not show corresponding collapse; and so it is clear that a subsidiary salt spine projected up into them and was dissolved out during the early part of Recent time, before the uplift of the present mound. But it is difficult to see how solution could have produced the observed effects at Clay Creek, where the thick massive

cap should preclude maximum solution at the center of the dome. The same objections apply to the explanation of the central syncline at Boggy Creek by this solution hypothesis. Slightly different patterns of slumpage of central synclines should be produced by retrograde movement of the salt-cap core and by solution of a static salt core. When more complete sections across such a dome as Clay Creek become available, it may be possible to determine which explanation is correct but on the basis of the present recognizably inadequate data, the writer inclines toward the belief in retrograde movement of or within the salt core as a phenomenon of the static old age of salt domes and as the cause of the central, super-cap depression of the sediments at the Clay Creek dome.

RIM SYNCLINES

Rim synclines are present on many of the salt domes of the interior group in Texas, for example, on the Mount Sylvan salt dome, Smith County, Texas.[17] But their presence on the domes on the Gulf Coast has not been recognized from geologic evidence. Certain inter-salt dome maxima in the Gulf Coast, however, are best explained by the presence of incipient rim synclines. The interferences of the two large minima which will be produced by two adjacent salt domes forms a gravity maximum between the minima. But the observed maximum between some domes is larger and sharper than the maximum which should be produced by the interference of the respective minima of the domes. The difference between that maximum and the observed maximum indicates a slight, abnormal excess of density at a depth less than 6,000 feet in the central area between two such domes as Esperson and South Liberty, Chambers County, Texas. Those abnormal inter-salt dome maxima can be explained by incipient rim synclines well out on the flanks of the domes.

Rim synclines theoretically can be of two different patterns, differing slightly in characteristics and produced by two different processes.

The process of formation of the inverted tear-drop form of the salt core should produce a rim syncline in the upper beds. The edge of the lower part of the flaring flank of the salt core, under the theory of upthrust, is pushed inward, ultimately to produce pinching off of the salt core; and under the theory of downbuilding, it is pushed inward and downward, likewise ultimately to produce pinching off of the root of the salt core. The displaced salt must be replaced by sediments. The volumetric displacement of the salt will be greatest over the lower

[17] E. A. Wendlandt and G. Moses Knebel, "Lower Claiborne of East Texas with Special Reference to Mount Sylvan Dome and Salt Movements," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (October, 1929), pp. 1347–75.

flank and will be *nil* at the crest of the salt core. The resulting subsidence of the sediments will be greatest well out from the edge of the crest of the salt core. That subsidence will not overbalance the steep dip of the deep flank sediments and will become evident as a syncline only in the uppermost horizontal, or very gently dipping flank beds.

Extensive retrogression of the flank of a static salt core under solution should produce a rim syncline. Sediments must replace the dissolved salt. The flank of the salt core normally dips steeply. The subsidence of the sediments should be concentrated in a rather narrow vertical zone. Solution, whether by moving water or by diffusion, should tend to decrease with depth. The retrogression of the flank of the salt under solution should tend to produce a rim syncline fairly close to the edge of the crest of the salt core.

The end point of that solution, however, should be a large central syncline. The upper part of the salt core ultimately should be completely dissolved and the rim syncline should develop into a central depression over the position of the now vanished or vanishing salt core. The formation of that central depression should be the last episode in the life cycle of a salt dome.

The rim syncline whose presence is suggested by the torsion balance survey of the Esperson dome, would be of the first type. Some of the downthrown blocks or graben next to the salt core, as for example at Spindletop and West Columbia,[18] may be the effect of the tendency toward the formation of the solution type of syncline, although a dynamic origin for them is not precluded.

OVERHANG

Overhang of the cap rock and of the uppermost part of the salt core is known to be present on several Gulf Coast domes, and probably is present on many others. The overhang on such a dome as Vinton is slight, but at Barbers Hill, it is at least 1,000 feet.

Two types of overhang presumably are present in the Gulf Coast.

Tilting of the axis of the salt core of several domes is surmised by the writer from geologic and gravity data. For commercial reasons, the data may not be presented at this time. They are scanty and not conclusive; yet from them, the writer surmises that tilting of the vertical axis of the salt core must be present. On the dome on which the data are the most conclusive, the overhang would seem to be on the side away from the gulf and the gentle slope on the side toward the gulf.

[18] D. P. Carlton, "West Columbia Salt Dome and Oil Field, Brazoria County, Texas," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 451–69.

The overhang at Barbers Hill goes essentially around the dome; and the upper part of the salt-cap core has somewhat the form of a mushroom.

Overhang of the upper part of the salt-cap core could be produced in several ways.

Dynamic overthrusting has slightly overturned many of the salt domes of old Roumania, but can not explain the overhang in the Gulf Coast.

Tilting of the axis of the salt core could be produced as the effect of flowage of the prism of unconsolidated sediments toward the unsupported edge of the continental shelf. This flowage should take place partly as an effect of the static pressure of the upper sediments on the lower sediments and, therefore, should be greater at moderate depth than at the surface. The salt core should move with the surrounding sediments; and the upper part of the salt core should move less than the part at moderate depth.

The flank of the salt core which has attained the form of a streamlined cylinder, overhangs; but for all practical purposes, the flank will be vertical within the depths which will be reached by the drill. And this type of overhang will not explain the observed overhang in the Gulf Coast domes.

Solution of the upper part of a static salt core ultimately will leave the cap overhanging. Greater solution at some general level than at higher levels also will produce overhang.

The overhang at Barbers Hill and its possible causes have been discussed by Judson. None of the suggested alternative theories of the formation of that overhang is convincing to the writer, but he has not found a more convincing theory to propose.

Résumé

The Gulf Coast salt domes have been formed by the plastic flowage of sedimentary salt intrusively upward into the overlying sediments. The evidence for that origin of the domes comes from the structure which is revealed by the oil-field drilling, from the algal remains in the salt, and from the close similarity of the American domes to the German domes.

The motive force of the formation of the domes must have been the static weight of the sediments. Growth of the domes has taken place throughout the Tertiary and has taken place on a few domes in the most recent geologic past. The motive force of the formation of the domes must be some force which has been active in the most recent geologic past. Evidence of dynamic tangential compression dur-

ing the Tertiary and Quaternary is wanting; and there is evidence for its absence. The motive force, therefore, can not be dynamic tangential compression, and by elimination must be the static thrust of the sediments.

Downbuilding must have been the predominant method of growth of the domes, for subsidence of the mother salt bed took place almost continuously throughout the Tertiary and Quaternary in the main Gulf Coast salt-dome area; therefore, growth of the domes by downbuilding must have taken place whether or not growth by upthrust also took place. But the difference between the specific gravity of the salt and the Gulf Coast sediments is small; and quantitative calculations indicate that the effective force of upthrust is small, rather too small to overcome friction, if energy has to be used to uplift the salt core and some sediments against gravity. Growth of the Gulf Coast domes presumably, therefore, must have been mainly by downbuilding. Partially corroboratory evidence is furnished by cessation of growth of the Clay Creek dome concomitantly with cessation of the previously prevailing regional subsidence in that area.

But actual upthrust has taken place in the Gulf Coast domes. Such a dome as Cote Blanche with Recent clays 100 feet above sea-level must have been upthrust within the very recent geologic past. And as one theoretically would expect, the larger domes show a tendency to be upthrust closer to the surface than do the small domes, for the frictional resistance between salt and sediments per volume of salt is less for a dome of large diameter than for a dome of small diameter; and the volume of the positively buoyant salt is larger on a large dome in reference to the volume of the negatively buoyant uplifted sediments.

Growth has not continued to present time on all the domes and has ceased finally on different domes at different times in the geologic past. Some domes show post-Pleistocene growth; others show active pre-Pleistocene growth and little or no post-Pliocene growth. Yet others show active pre-Pliocene growth and little or no post-Miocene growth. And yet others show active pre-Miocene growth and little or no post-Oligocene growth, and so on. Growth of the Clay Creek dome ceased with the end of the Eocene. The crude law holds that the growth of shallow domes persisted into the late Tertiary; that the growth of deep domes ceased in the middle of the Tertiary; and that the growth of the very deep domes in general ceased in the early Tertiary. But one may not say that the age of cessation of growth is directly proportional to depth, for at the Orange (very deep)

dome, there has been at least 1,000 feet of Miocene structural uplift of Lower, Middle, and Upper Oligocene beds.

Final cessation of the growth of salt domes may be caused by (1) exhaustion of the salt in the mother salt bed; (2) attainment of isostatic equilibrium; (3) frictional freezing of the salt core to the sediments; and (4) in the case of growth by downbuilding, cessation of the regional subsidence. The last cause presumably was the effective one at Clay Creek, but can not have been effective on the domes much nearer the coast except in post-Pleistocene time.

Retrograde, downward movement of the salt core or at least of the upper part of the salt core is suggested by the Clay Creek dome as following the cessation of growth, although the evidence is not conclusive. The explanation is complicated and unsatisfactory.

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OIL FIELDS OF POLAND, GEOLOGICAL AND STATISTICAL SUMMARY[1]

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ABSTRACT

The present article is a tabulated summary of the geological and statistical features of Poland's oil fields as of April, 1933, and may be regarded as a continuation of an article by the same author, published in the *Bulletin of The American Association of Petroleum Geologists*, November, 1932.

INTRODUCTION

The oil and gas fields in the Carpathians of South Poland lie in an area where two provinces are recognized: (1) the sub-Carpathian province embracing the gentle mountainous area in front of the orographically exposed Carpathian ridge, and (2) the Carpathian province. The first province—from the point of view of geological structure—represents areas constituting a tectonic unit of the first order or a part of the foreland depression in front of the margin of the Carpathian folding, whereas the second province comprises an entire complex of geologic units of diversified structure.

In the sub-Carpathian province prevail only Miocene formations, under which are concealed the primordial folds of the Carpathians composed of Oligocene. Until now only gas fields have been discovered in this area (Daszawa, Kalusz), covering in Daszawa an area of several thousand hectares.[3] Test drilling, having for its object the investigation of the lower sequence of the Miocene (the upper series of which contains the gas horizons), has been commenced by the Pionier Company. The first test well was located near Rachin, southeast of the Daszawa gas fields, after this part of the sub-Carpathian depression had been investigated by the seismic and magnetic methods. On the basis of geological considerations, this part of the sub-

[1] Manuscript received, May 4, 1933. Supplement to "Geology and Mining of Petroleum in Poland," by same author, published in the *Bulletin*, Vol. 16, No. 11 (November, 1932), pp. 1061-91.

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[3] One hectare equals 2.471 acres.

Carpathian province, which comprises an area between the meridian of Boryslaw and Kosow, that is, an area of not less than 5,000 square kilometers (500,000 hectares, or 1,235,500 acres) represents the greatest possibilities as regards prospecting work, and may be accepted as possible oil land.

The Carpathian province consists of 3 zones of a different structure: the Marginal zone along the sub-Carpathian depression, the Median zone or a distinctly marked longitudinal depression lying between the slightly more elevated Marginal zone on the northeast and a likewise elevated zone on the southwest, or Magura zone, which passes into the Czechoslovakian territory.

SUMMARY

The area of the Marginal zone (Fig. 1) in its more precise limits, between the slice of Skole and the edge of the sub-Carpathian depression, occupies approximately 240,000 hectares: the producing, proved (not all of economic value), and probable lands within this area comprise approximately 3,430 hectares, or 1.5 per cent of the total area.

The area of the Median and Magura zones, within very broad limits, occupies about 1,454,400 hectares, of which from the town of Nowy Sącz on the northwest to Zabie on the southeast, near the Bukowina frontier, there is approximately 0.6 per cent of the total area. Of the tremendous area of the Carpathian petroliferous province, 97.8 per cent has not been tested at all commercially. A large part of this area, composed of complexes of slices (*skiby*) or of deeply folded formations of secondary longitudinal depressions of synclinal structure, or of folds of the diapiric type, is not promising for oil prospecting. However, within the area of the Median zone and on the northern portions of the Magura zone, there may be areas suitable for test drilling with the object of discovering new oil horizons (Cretaceous) deeper than the horizons already proved. Producing and proved lands do not exceed 3,000 hectares, and are therefore considerably less than Tolwinski's calculations.[4] The area of producing oil fields of the Carpathian province amounts to 7,300 hectares. The difference between our calculation of the producing and proved lands (3,000 hectares) and the foregoing figure covering producing land (7,300), is 4,300 hectares, representing approximately the area of semi-proved land. It is estimated that 97.8 per cent of the area of the Carpathian province should be classified as commercially unproved

[4] *Statistique du Pétrol en Pologne* (1932).

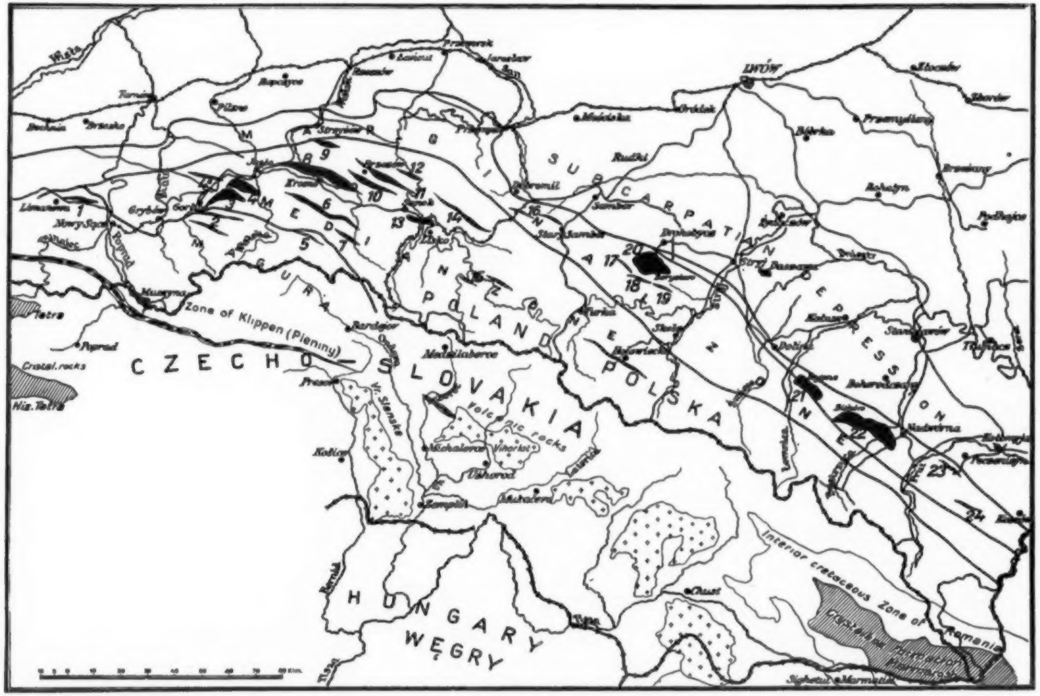

FIG. 1.—Oil fields of Polish Carpathian Mountains. *1.* Klęczany. *2.* Ropa-Szymbark-Siary-Męcina-Ropica. *3.* Dominikowice-Kobylanka-Libusza-Kryg. *4.* Harklowa-Wójtowa. *4a.* Biecz-Załawie-(Korczyna). *5.* Ropianka-Smereczna-Wilsznia-Komornik (Czechoslovakia). *6.* Bóbrka-Wietrzno-Równe-Rogi. *7.* Rudawka Rymanowska-Tokarnia-Wola Sękowa. *8.* Sądkowa-Białkówka-Brzezówka-Męcinka-Jaszczew (gas fields) and Potok-Toroszówka-Krosno-Krościenko-Trześniów (oil fields). *9.* Węglówka. *10.* Zmiennica-Turzepole-Strachocina. *11.* Starawieś-Brzozów-Humniska-Grabownica. *12.* Izdebki-Witryłów. *13.* Zagórz and vicinity. *14.* Stańkowa-Paszowa-Ropienka-Wańkowa-Leszczowate. *15.* Rajskie-Polana and vicinity. *16.* Starzawa-Stara Sól-Strzelbice. *17.* Opaka. *18.* Schodnica. *19.* Pereprostyna-Urycz. *20.* Borysław-Tustanowice-Mrażnica. *21.* Rypne-Duba-Perehińsko. *22.* Majdan-Rosulna-Bitków-Pasieczna. *23.* Słoboda Rungurska. *24.* Kosmacz.

Map shows three tectonic zones, each overthrust northeast toward sub-Carpathian depression (foreland): (1) Magura (not oil-bearing excepting in tectonic inliers), (2) Median (oil in Cretaceous-Oligocene), (3) Marginal (oil in Cretaceous-Oligocene). In sub-Carpathian depression gas is produced from Miocene. East-west length of area mapped, approximately 236 miles.

land; part of these lands may represent possible oil lands, but it is impossible to express this in figures.

In order to make a correct appraisal of these lands, it should be taken into consideration that the production of 1 hectare of the 2,516 hectares of the producing area is estimated since the beginning of the industry at 1,200 cars[5] (total volume of oil produced hitherto in Poland, 3,069,758 cars). Tolwinski estimates that the oil fields of Poland are not exhausted, and that with an improved method of exploitation they may yield a maximum of 100 tank cars per hectare. In view of the foregoing, from 7,300 hectares of producing and proved land, he could expect about 7,300×100 cars, or 730,000 cars. According to our calculations the reserves on producing and proved lands do not exceed 500,000 cars. It should, however, be kept in mind that 75 per cent of the entire production in the Carpathians was obtained in the Boryslaw-Tustanowice-Mraznica fields, having an area of 1,140 hectares, or only about 45 per cent of the total area of the producing oil fields; therefore, this possible reserve could be lifted only during a very long period of time. If the average decline in production of 7 per cent for the past 5 years is taken as a basis for estimating the entire reserve to be lifted, this reserve would be exhausted within 17 or 18 years.

The geological surveys in the Carpathians have progressed already to such an extent since 1924 that it may be asserted that in the unproved area mentioned (97.8 per cent of the Carpathians) there are only local forms of structure suitable for prospecting oil horizons of minor industrial importance. Several wells drilled recently by the Pionier Company and other firms on such favorable structure gave negative results.

In order to appraise the possible oil reserves in the Carpathians, therefore, 97.8 per cent of the area should be entirely eliminated.

[5] One tank car of oil equals 10 metric tons, or approximately 74 barrels.

OIL FIELDS OF POLAND (GEOLOGICAL AND STATISTICAL SUMMARY)

JASLO DISTRICT—MAGURA ZONE[1]

Oil Fields[1]	*Columnar Section and Oil Horizons*			*Structure*	*Area (Hectares)* 1. *Producing* 2. *Proved* 3. *Probable*	*Depths of Wells (Meters)*
	Oligocene	*Eocene*	*Cretaceous*			
	Magura Sandstones	*Red and green shales with sandstones*	*Ropianka beds and black shales, bituminous*			
1. Klęczany and vicinity			Sandstones in Ropianka beds	One complex of series supposed to be overthrust on facies of Median zone, confirmed near north margin of Magura zone, near Kryg, Harklowa, Pagorzyna. Oil fields are on marginal parts of Magura unit. Lower Cretaceous series not sufficiently explored	1. 30 2. — 3. 120 Oil trend 12 km. lo	200
1a. Posadowa and vicinity			Same		1. 5 2. — 3. 160 Oil trend 16 km. lo	450–551
2. Szymbark, Siary, Sękowa, Męcina Wielka, Ropica Ruska			Same		1. 30 2. — 3. 4,000 Many groups	150–435
5. Ropianka			Same		1. 10 2. 20 3. 300	300–569

[1] Location of geologic or tectonic zones, and oil and gas fields, shown by corresponding number on Figure 1.

Depths of Wells (Meters)	*Number Producing Wells, Jan. 1, 33*	*Number New Drilling Wells, 1932*	*Initial Production (Kilograms)*	*Early Prod., Cars, 1932*	*Number Wildcat Wells, 1932*	*Crude Oil*		*Remarks* *Yield Cumulative, Dec. 31, '32* *Reserves Estimated, Cars*
						Density	*Quality*	
200	1	—	—	2	—	a. 0.870 b. 0.780	Lubricating and vaseline Gasoline, 22% Some paraffine Gasoline, 43%	Yield? Reserves?
450–551	2	—	—	2	—		Paraffine Gasoline, 22%	Yield? Reserves?
150–435	48	5	1,000–2,500	180		a. 0.822 0.828 b. 0.850 0.857	Paraffine Gasoline, 30% Lubricating Gasoline, 30%	a. Szymbark b. Męcina Wielka, Sękowa, Ropica Ruska. Yield? Reserves, 3,000
300–560	12			30		a. 0.720 b. 0.850	Non-paraffine Gasoline, 32%	Yield, 1,800 Reserves, 4,000 (?)

JASLO DISTRICT—

Oil Fields	Columnar Section and Oil Horizons			Structure	Area (Hectares)
	Oligocene	Eocene	Cretaceous		
	Krosno beds and menilite slates	*Red and green shales with sandstones (Ciężkowice)*	*Black shales with sandstones*	*Folds on parts of greatest culmination in middle of great inter-Carpathian depression, but local structure in each field*	1. Producing 2. Proved 3. Probable
3. Dominikowice, Kobylanka, Libusza, Lipinki, Kryg	I horizon in Krosno beds	Ciężkowice sandstones II–III. Porosity, 23–24%. Thickness of sandstones, 5–18 meters	IV horizon sandstones in black shales	One large fold in front of marginal part of Magura zone	1. 150 2. 50 3. 300
4a. Harklowa b. Pagorzyna c. Biecz	a. Krosno beds	Ciężkowice sandstones I–II. Thickness of sandstone series 15–19 m. with few oil sands, 2–3 meters		At Hraklowa and Pagorzyna below Eocene cover overthrust from south. Biecz, diapiric fold inclined north	1. 40 2. 15 3. 100
6a. Bóbrka b. Wietrzno c. Równe d. Rogi		II–III. Ciężkowice sandstones. Thickness, sandstone series: I, 120 m.; II, 50 m.; III, 50 m., with 20–30% oil sands	In western part, Cretaceous sandstones, IV horizon	Fold 25 km. long, inclined north, refolded at some points and broken by groups of faults	1. 60 2. 10 3. 200
7a. Lubatówka, Iwonicz b. Klimkówka-Wólka, c. Rudawka Rymanowska		II–III Ciężkowice sandstones (Main horizon, III)	Cretaceous sandstone (IV)	Unsymmetrical fold inclined north on sections *a* and *b*, and overturned on section *c*. On this section, Krosno beds covered by menilite slates and Eocene beds of core of entire fold	1. 30 2. 20 3. —
	c. Krosno beds	Thickness, sandstone series: I, 150 m.; II, 90 m.; III, 60 m.; IV, 80 m. with 20% oil sand		Fold-axis is most culminated at Wulka and dips NW. under oil fields at sections *b* and *a*. Fields on section *b* flooded by top water and contamination averages 60%. On section *a* edge water is confirmed	
8. Roztoki, Męcinka, Potok, Toroszówka, Białobrzegi, Krościenko, Niż. Haczów Trześniów		Ciężkowice sandstones I–II. I sandstone, gas horizon II gas and oil horizon. Thickness of sandstone series: I, 50 m. II, 30–80 m.	III sandstones only in Męcinka, Białkówka, Jaszczew	Diapiric and closed fold 40 km. long broken by transverse faults into separate blocks, some already flooded. Great fold in many places refolded into minor folds	1. 70 2. 10 3. 400 Width, producing area, 100–200 m.

MEDIAN ZONE

Depth of Wells (Meters)	*Number Producing Wells Jan. 1, '33*	*Number New Drilling Wells 1932*	*Initial Production Kilograms*	*Early Prod., Cars, 1932*	*Number Wildcat Wells, 1932*	*Crude Oil*		*Remarks Yield Cumulative, Dec. 31, '32 Reserves Estimated, Cars*
						Density	*Quality*	
obylanka, 450; ibusza, Lipinki, 0-460; Kryg, 0-400	352	20	500–5,000	1,744	—	a. 0.857 b. 0.833	Paraffine (black oil) Lubricating (green oil)	a. Libusza, Lipinki b. Kobylanka, Kryg Yield, 31,855 Reserves, 15,000
300 630	149	a. 8 b. — c. 4	1,000 3,000	1,065	1*)	a. 0.885 Depth 372 m. b. 0.826 c. 0.822	Lubricating (paraf., 0.5%) Gasoline, 9–12% Some paraffine Gasoline, 16% Non-paraffine Gasoline, 24–42%	*) Ropita 24 at Harklowa: 1,009 m., Krosno beds: drilling At Sobniow among Harklowa fields and Potok-trend: one wildcat in 1931 stopped at 1,333 m. in lower Krosno beds Yield, 18,800 Reserves, 7,500
330–1,132	a. 29 b. 16 c. 21 d. 3 69	4	Wells N 53 at Równe, 10,000. Depth, 670 m.	1,532	2(*)	II, Rogi, 0.839 Równe, II, 0.859 Depth, 609 m. IV, 0.874	Non-paraffine Non-paraffine (0.30%) Gasoline, 33% Paraffine (from dipper horizon)	(*) At Załeże and Wola Dębowiecka on part of fold dipping NW.: drilling at 700 m. Yield, 69,600 Reserves, 14,000
385–694 250–560 330–968	a. 17 b. 42 c. 3 62	— — —		a. 157 b. 165 c. 5		a. I, 0.920 0.950 II, 0.780 0.790 III, 0.820 0.840 b. 0.876 0.881 c. 0.843	Gasoline Lubricating Gasoline, 20.5% III sandstone Lubricating Gasoline, 20% Paraffine Gasoline, 6.5%	Yield, 23,700 Reserves, 8,000
700–900 920–1,123 tok, 557–640 ościenko, 300–500	129	7	Potok: only gas, 35 m.³/m. Toroszówka: 2 wells, edge water	2,130	1(*)	a. Potok: depth, 735 m., 0.822, depth, 1,050 m., 0.840 b. Krościenko: depth, 518 m., 0.888 c. Winnica: light oil d. Toroszówka: 0.790 0.700	Non-paraffine (0.23%) Gasoline, 16–17 and 35% Lubricating Lubricating (paraff., 0.3%) Gasol., 16% Non-paraffine Gasoline, 25% Non-paraffine Gasoline, 60, 54%	*) Wildcat at Roztoki: depth, 1,041 m. gas, 10 cubic meters per minute Closed pressure, 90 atm. Reserve gas on 20 hectares(?), 1 billion cubic meters Yield, 76,000 Reserves, 10,000

JASLO DISTRICT—MEDIAN ZO

Oil Fields	Columnar Section and Oil Horizons			Structure	Area (Hectares) 1. Producing 2. Proved 3. Probable	Depth of Wells (Meters)
	Oligocene	Eocene	Cretaceous	Folds on parts of greatest culmination in middle of great inter-Carpathian depression, but local structure in each field		
	Krosno beds and menilite slates	Red and green shales with sandstones (Ciezkowice)	Black shales with sandstones			
9. Węglówka			Two horizons, at some points three (sandstones of Czarnorzeki)	Two parallel folds pinched out and inclined north, emerging in presumable tectonic window (inlier)	1. 52 2. 20 3. 50	150–300 Thirty horiz –450
10a. Zmiennica b. Turzepole c. Strachocina		Ciężkowice sandstones I–II	Sandstone of III horizon	Diapiric fold; in some places refolded; many transverse faults	1. 15 2. — 3. 350	360–510
11a. Starawieś b. Brzozów c. Humniska d. Grabownica e. Trepcza		Ciężkowice sandstone, only one horizon	Two sandstones	Diapiric narrow fold with many transverse faults	1. 40 2. 10 3. 200	300–985 1,003
12. Izdebki, Witryłów		Ciężkowice sandstone		Fold inclined north	1. 8 2. — 3. 500	300–400
13. Zagórz, Tyrawa Solna, Mokre (Tarnawa Dolna)	Sandstones in Krosno beds			Few pinched folds extending farSE.	1 20 2. — 3. 125	300–400
				Total Jaslo District	1. 560 2. 155 3. 6,805	

DROHOBYCZ DISTRICT—MEDIAN Z

Oil Fields	Columnar Section and Oil Horizons			Structure	Area (Hectares) 1. Producing 2. Proved 3. Probable	Depth of Wells (Meters)
	Oligocene	Eocene	Cretaceous			
	Krosno beds and menilite slates	Red and green shales with sandstones (Ciezkowice)	In some places, facies of Inoceramus beds			
14a. Wańkowa, Brelików, Leszczowata b. Ropienka c. Paszowa, Stańkowa	Few horizons in Krosno beds (lower) and menilite slates (upper)	Thickness of oil sands: a. 10–2 m. b. 12–2 m. c. 7–2 m.		Diapiric fold, with southern limb overturned south. Narrow (100–200 m.) producing area 12 km. long	1. 100 2. 80 3. 200	200–400
15a. Rajskie b. Polana and vicinity	Same			Few pinched folds inclined north	1. 16 2. 10 3. 300	300–400

RICT- EDIAN ZONE (Continued)

Depth of Wells (Meters)	Number Producing Wells, Jan. 1, '33	Number New Drilling Wells, 1932	Initial Production (Kilograms)	Early Prod., Cars, 1932	Number Wildcat Wells, 1932	Crude Oil		Remarks Yield Cumulative, Dec. 31, '32 Reserves Estimated, Cars
						Density	Quality	
150-300 Thirty horizon -450	82			387		Depth, 450 m., 0.867	Non-paraffine (0.44%) Lubricating Gasoline, 23%	Oil field flooded by top water. Yield, 24,600 Reserves, 7,000
360-510	30	b. 4	210-1,200	272	2 *)	a. 0.853 b. 0.861	Paraffine Non-paraffine	*) Strachocina, only gas; in 1932, 2,427,000 m.³ (reserve gas, 500,000,-000 m.³). Yield, 8,000 Reserves, 2,000
300-985 1,003	a. 4 b. 5 c. 17 d. 26 — 52	a. 1 b. 1 d. 1	b. 1,400 d. 2,500	a. 287 b. 124 c. 213 d. 938 — 1,562	e. 1(*)	a. 0.725 b. 0.805 c, d. Depth, 564 m., 0.822	Non-paraffine Some paraffine Gasoline, 36% Non-paraffine Lubricating Gasoline, 35%	*) One wildcat at Trepcza, drilling Yield, 18,332 Reserves, 5,000
300-400	4			22	1*)		Paraffine Gasoline, 31%	*) Wildcat at Izdebki (Pionier): drilling, 854 m.
300-400	5	2	250-900	65		Light. Mokre: 0.812	Non-paraffine Gasoline, 43%	Yield, 15,630 Reserves, 100 (?)
	997	57		9,320	8			Yield, 288,317 Reserves, 75,600

ISTRIC EDIAN ZONE

Depth of Wells (Meters)	Number of Producing Wells, Jan. 1, '33	Number New Drilling Wells, 1932	Initial Production, (Kilograms)	Early Prod., Cars, 1932	Number Wildcat Wells, 1932	Crude Oil		Remarks Yield Cumulative, Dec. 31, '32 Reserves, Cars
						Density	Quality	
100-400	a. 164 b. 71 c. 33 — 268	a. 6 b. 3 c. 5 — 14	a. 2,000-2,500 b. 130-3,200 c. 1,300-2,000	a. 1,549 b. 245 c. 139 — 1,933	1 *)	a. 0.863 b. 0.872-0.844 c. 0.840 0.856 0.818	a. Paraffine (4.4-5.7%) Gasoline, 17% b. Paraffine (4.4%) Gasoline, 16-19% c. Some paraffine (0.6-0.9%) Stańkowa: lubricating Gasoline, 29%	*) Wildcat at Wańkowa (Brelików) on N. limb, dry (1,000 m.) Yield, 69,826 Reserves, 16,000
300-400	8	b. 1	8,000	37		a. 0.786 b. 0.834	Non-paraffine Gasoline, 48% Paraffine Gasoline, 14%	Yield, 720 Reserves, 500

DROHOBYCZ DISTRICT ARGINAL

Oil Fields	Columnar Section and Oil Horizons: *Oligocene*	*Eocene*	*Cretaceous*	Structure	Area (Hectares) 1. Producing 2. Proved 3. Probable	Depth of Wells (Meters)
	1. *Polanica beds (shales with sandstones)* 2. *Menilite slates with Kliwa sandstone and two series of hornstones. Under menilites, Boryslaw sandstone*	3. *Popiele beds (shales and sandstones)* 4. *Green and red shales with sandstones (upper Hierogliph beds)*	5. *Jamna sandstones* 6. *Inoceramus beds (shales, slates, and sandstones — lower Hieroglyph sandstones)*	*Few complexes of folds inclined north and overthrust (Skiba in Polish)*		
16. Starzawa, Stara Sól, Strzelbice		In sandstones of the series 4	In upper beds of Jamna sandstone	Two unsymmetric folds; southern overthrust on northern. Oil fields only on southern	1. 30 2. 10 3. —	250–300
17. Opaka		Sandstones of upper Eocene and two horizons in series 4		Pinched fold, steep dip of beds. Narrow producing area (100 m.)	1. 20 2. 10 3. —	350–750
18. Schodnica		In Eocene sandstones only weak horizons	Main horizon in Jamna sandstone (thickness—80 m.). Also Cretaceous sandstone	Unsymmetrical fold on extension of great transverse Boryslaw culmination. Fold squeezed in two complexes of slices (*skiba*)—from N. of Mraźnica (Orów), and from S. of Skole. Fold dips SE. and emerges NW. toward Opaka	1. 200 2. — 3. —	204–230 xis culmin 500–1,00 on S. limb
19. Urycz, Pereprostyna		Same	Same	Lengthening of Schodnica fold	1. 100 2. 50 3. —	300–450

DROHOBYCZ DISTRICT ARGINAL

Oil Fields	Columnar Section and Oil Horizons	Structure	Area (Hectares) 1. Producing 2. Proved 3. Probable	Depth of Wells (Meters)
20a. Boryslaw b. Tustanowice c. Mraźnica	Oil horizons in beds of overthrust (*Inoceramus* beds, I) and in any series of great deep fold (Polanica beds, II; menilite slates, III; main horizon Boryslaw sandstone, IV; upper Eocene, V; lower Eocene and Jamna sandstone, VI) Water horizons in Polanica beds (salt water in many places under high pressure), salt water in lower Eocene and Jamna sandstone Edge water in Boryslaw sandstone and Eocene beds encroaches from SE. and S. Thickness of oil sands: IV, 10–35 m., few 50–80 m. In S. part Mraźnica, Boryslaw sandstone is divided in two beds by slate beds (thickness, 3–9 m., few 19–21 m). Total thickness Boryslaw sandstone, 50–54 m. Porosity, productive sandstone: IV, 10.50–15.32%; V, 9.79–12.17%. Porosity, dry sandstone: IV, 5.29–6.34–8.53–15.80%; V, 3.94–4.32%; Jamna sandstone, 10.20%	Deep recumbent fold overturned N.; middle limb detached and thinning. Frontal bend of fold squeezed into Miocene salt, which in N. part of fold lies conformably on Polanica beds; in S. part lie unconformably (overthrust) packs of slices (*skiba*) of Orów and Marginale Max. deformation on line of great transverse culmination of Carpathians. S. limb of total fold is refolded in minor culminations and depressions. Deformations and difference in permeability of sandstones are shown by pools in one large field Entire structure complicated by few transverse faults: Popiele fault limits field on NW.; axis fold dips SE. From SE., partly from S. field completely flooded	1. 1,140 2. — 3. 300 at Orów	V, 1,300–1 V, 1,600–1, V, 1 200–1 V, 1,400–1, V, 1,550 V, 1,700–1, 160–960 (overthrust
	Oligocene | *Eocene* | *Cretaceous*			
21a. Duba b. Rypne c. Perehińsko	*Oligocene*: In Kliwa sandstones three horizons	Two folds of menilite series overturned N. and overthrust by Eocene beds of marginal part of zone of slices (*écailles*)—Skole	1. 50 2. 30 3. 300	Old fields 150–300 New fields 500–600, 700–856
		Total Drohobycz district	1. 1,656 2. 190 3. 1,100	

ISTRICT ARGINAL ZONE

ectares) lucing ed able	Depth of Wells (Meters)	Number Producing Wells Jan. 1, '33	Number New Drilling Wells, 1932	Initial Production (Kilograms)	Early prod., Cars 1932	Number Wildcat Wells, 1932	Crude Oil		Remarks Yield, Dec. 31, '32, Cars Reserves, Cars
							Density	Quality	
	250–300	38	2	1,000–6,000	358 (only Strzelbice)		0.862 0.872	Paraffine (6.2–6.6%) Gasoline, 14–18%	Yield, 7,115 Reserves, 3,000
	350–750	5			58		0.835 0.808–0.817	Paraffine Gasoline, 25% Gasoline, 30%	Yield, 1,500 Reserves, 1,000
	204–230 xis culmination 500–1,000 m. on S. limb	366	5	1,500–2,400	3,616		a. 0.826 0.829 0.839 b. 0.867 0.871 c. oil from Inoceramus beds, 0.808	Non-paraffine (0.23%) Gasoline, 29–34% Lubr. (0.23%) Gasol. (13–23, 31%) Paraffine	NW. part of fold SE. part of fold Yield, 203,935 Reserves, 40,000 At Schodnica, air and gas lift successfully commenced
	300–450	139	1	3,400	826		Depth, 356 m., 0.874 0.887	Lubricating (paraf., 0.15%) Gasoline, 20–24%	Yield, 43,470 Reserves, 7,000

ISTRICT ARGINAL ZONE (Continued)

Hectares) ducing ved bable	Depth of Wells (Meters)	Number Producing Wells, Jan. 1, '33	Number New Drilling Wells, 1932	Initial Production (Kilograms)	Early Prod., Cars, 1932	Number Wildcat Wells, 1932	Crude Oil		Remarks Yield, Dec. 31, '32, Cars Reserves, Cars
							Density	Quality	
at Orów	V, 1,300–1,500 V, 1,600–1,700 V, 1 200–1,400 V, 1,400–1,500 V, 1,550 V, 1,700–1,800 160–960 (in overthrust)	a. 132 b. 223 c. 133 488 and gas wells only	a. 2 b. 6 c. 7 15 and wells only in dipping	a. 5,000–8,000 b. dry c. 4,500–24,000	a. 8,533 b. 11,516 c. 12,980 33,029 c. shallow wells 205 33,234	4*)	a. IV, depth, 1,472 m., 0.850 b. IV, depth, 1,356 m., 0.852 c. IV, depth, 1,454 m., 0.860 c. III, 1,699 m., 0.869	Paraffine, 8.9% Gasoline, 19.20% Paraffine, 9.6% Gasoline, 20.68% Paraffine, 9.3% Gasoline, 17.27% Paraffine, 7.7% Gasoline, 16.54%	*) 1. Stateland South: 2,085 m.; upper Eocene; edge water 2. James Forbes: 2,030 m.; upper Eocene; edge water 3. Minister Kwiatkowski: 1,700 m.; under overthrust in lower Polanica and menilite; gas and oil (10,000 kg./day) 4. Orów on tectonic unit SE. from Boryslaw: 1,738 m.; Polanica beds, under overthrust Yield, 2,316,480 Reserves, 300,000
	Old fields, 150–300 New fields, 500–600, 700–856	a. 27 b. 76 c. 2 105	a. 1 b. 2	dry dry	a. 521 b. 1,404 c. 5 1,930		0.841 0.838	Non-paraffine Gasoline, 22%	Yield, 21,350 Reserves, 28,000
		1,417	41		41,992 Other small pools, 54 42,046	5			Yield, 2,664,396 Reserves, 395,500

STANISLAWOW DISTRICT—MARGINA

Oil Fields	Columnar Section and Oil Horizons: Oligocene	Columnar Section and Oil Horizons: Eocene	Columnar Section and Oil Horizons: Cretaceous	Structure	Area (Hectares) 1. Producing 2. Proved 3. Probable	Depth of Wells (Meters)
	1. Salt formation and Polanica beds *2. Menilite slates with few beds of Kliwa sandstones*	*3. Green shales with beds of sandstone* *4. Sandstones and limestones* *5. Green and red shales* *a. Quartzitic sandstones (upper hieroglyph beds)*	*6. Jamna sandstones* *7. Red plat beds (shales)* *8. Inoceramus beds (shales and sandstones)*			
22a. Majdan, Rosólna, Kryczka		Two (I–II) horizons in beds 3. Thickness of series: I, 80 m.; II, 70 m.		Unsymmetrical fold of series 1–2–3–4 overturned north	1. 20 2. 20 3. 100	I, 180–26 II, 330–50
b. Bitków	In series 1, horizon I; in series 2, II, III, IV horizons. Thickness of sands: II, 5–12 m.; III, 3 m.; IV, 5–8 m.		In series 7, horizon 0	Structure of two tectonic units: unsymmetrical fold of sheared series 1–5 (deep element) and great refolded overthrust of series 3–8. Longitudinal fault divides field into two parts: old field on N.; new field on S.	1. 100 2. — 3. 600	Old fiel 500–1, New fie 900–1,
c. Pasieczna	Horizons II and IV		Horizon 0 in series 7–8	SE. lengthening of both Bitków elements. Old field is only on series 7–8. New field—section Chrobry	1. 70 2. — 3. 100	Old fiel 250–35 New fie 900–1,
23. Słoboda Rungurska			In series 7–8, three horizons; III, main; thickness, sandstone series, 66 m.	Unsymmetrical fold overturned north; axis of fold plunges NW.	1. 100 2. — 3. —	200–32
24. Kosmacz			I–II–III horizons in series 8. Thickness, sandstone series: I, 10 m.; II, 30 m.; III, 20 (main horizon)	Unsymmetrical fold with axis plunging NW.	1. 10 2. — 3. 50	385–60
				Total Stanisławów District	1. 300 2. 20 3. 850	
				Total Poland	1. 2,516 2. 365 3. 8,755	

SUBCARPATHIAN DEPRESSIO

Drohobycz District Gas Fields	Columnar Section and Gas Horizons: Miocene, Middle	Columnar Section and Gas Horizons: Miocene, Lower	Columnar Section and Gas Horizons: Oligocene, Upper	Structure	Area (Hectares) 1. Producing 2. Probable	Depth of Wells (Meters)
	1. Cerithium beds, shales and sands (Pokucie beds) *2. Red marls with saliferous beds (Stebnik beds)* *3. Series of gray shales and sandstones (Dobrotów beds)*	*4. Salt-bearing shales and clays (salt formation) with conglomerates of Sloboda Rungurska, Truskawiec*	*5. Polanica beds* *6. Menilite series*	*At Carpathian marginal front many pinched folds overturned N., few S.; in middle of depression folds more gentle. According to some geologists, structure of saline-plug (dome) type also may be expected, independent of Carpathian folding*		
a. Daszawa	Thickness main gas horizon, 16 m.			Flat dome of beds of 2–3 series, with lengthening NW. Few salt-water horizons above main gas horizon	1. 160 2. Very great	685–7
b. Gelsendorf	Thickness, main gas horizon, 15 m.			Gas series belongs to Tortonian above Stebnik beds. Saliferous beds with potassium and common salts occur in 3 levels: (1) Cerithium beds; (2) Stebnik beds (middle Miocene); (3) lower Miocene (Helvetian)	1. 100 2. Great	760–7
c. Kałusz						

TRICT—[M]ARGINAL ZONE

...ctares) ...cing ...d ...ble	*Depth of Wells (Meters)*	*Number Producing Wells, Jan. 1, '33*	*Number New Drilling Wells, 1932*	*Initial Production (Kilograms)*	*Early Prod., Cars, 1932*	*Number Wildcat Wells, 1932*	*Crude Oil*		*Remarks Yield, Dec. 31, '32, Cars Reserves, Cars*
							Density	*Quality*	
	I, 180–260 II, 330–500	59	7	1,000	356		0.832–0.836	Lubricating Gasoline, 24–40%	Yield, 3,300 Reserves, 3,000
	Old field, 500–1,000 New field, 900–1,500	100	3	2,000 12,000**)	2,812	1*)	Old field: depth, 715 m., 0.808 New field: depth, 1,155 m., 0.827	Paraffine (3.4%) Gasoline, 33% Paraffine(3.6%) Gasoline, 25%	*) In SE. part of old field deepening to 1,220 m., unsuccessful. **) Dąbrowa (Małop.) N 52. Yield, 68,200 Reserves, 17,000
	Old field 250–350 New field, 900–1,200	28	2	300–400	534		Chrobry 3: depth, 1,129 m., 0.810 Chrobry 4: depth 1,118 m., 0.838 Old field: 0.728	Paraffine, 2.34% Gasoline, 32% Paraffine, 4.91% Gasoline, 26% Non-paraffine Gasoline, 67%	Yield, 8,735 Reserves, 5,000 Gas field in southern part
	200–320	50			212	1*)	Depth, 164 m., 0.850 Depth, 311 m., 0.839	Paraffine, 3.5% Gasoline, 22.5%	*) At Czarny Potok Pionier's wildcat: drilling, 846 m.; from 800 m. in Jamna sandstone; flooded Yield, 34,205 Reserves, 2,000
	385–600	10			54		0.887	Non-paraffine Gasoline, 7%	Yield, 2,605 Reserves, 1,000
		247	12		3,968	2			Yield, 117,045 Reserves, 28,000
		2,661 in meters 58,478 (−21.5% from 1931)	110		55,596 (−11.7% from 1931)	15			Yield, 3,069,758 Reserves, 499,100

...ARPATHI[AN D]EPRESSION

(Hectares) ...ducing ...bable	*Depth of Wells (Meters)*	*Number Producing Wells, Jan. 1, '33*	*Number New Drilling Wells, 1932*	*Initial Production in m.³/m. and Pressure in Atmospheres*	*Early production 1932, in Thousand Cubic Meters per Minute*	*Number Wildcat Wells*	*Remarks*
great	685–760	10	2	300 57–60 atm.	96,187	1*)	*) At Rachiń (Pionier): drilling at 836 m.; Stebnik beds
t	760–775	4	1	200 58 atm.			a–b. Reserves of produc. area about 4 billion cubic meters
						1*)	*) At Grabówka near Kałuszi preparation (Pionier)

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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PSEUDO-TECTONIC STRUCTURES[1]

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ABSTRACT

In parts of Australia and New Guinea, what are apparently normally folded rock structures have been encountered in areas where exposures are poor, owing either to profound weathering or to dense jungle. It has been shown that much of this "false folding" is due not to tectonic forces, but to local effects including (1) swelling of argillaceous members, (2) plastic flow of bentonitic beds, and (3) concretionary development on an unprecedented scale. Possibly certain anomalous "folds" in other regions may be of the same nature.

In the course of geological work in various parts of Australia, the writer has been confronted by seeming paradoxes which have caused much loss of time and money in geological survey and in fruitless drilling for oil of apparent "domal structures." Only recently has the explanation been forthcoming. Receipt of the admirable work of Carey Croneis, "Geology of the Arkansas Paleozoic Area with Especial Reference to Oil and Gas Possibilities"[3] has suggested that somewhat analogous phenomena may be more widespread than usually believed, and that some of the difficulties encountered in Australia may be paralleled in other fields, without recognition of their exact significance.

Many years ago the writer described certain apparent fold features in the coal seams of southern New South Wales, and explained them as due to expansion of shaly beds associated with the coal seams. As that paper[4] was published locally, and is not easily accessible to workers in other countries, the main facts may be summarized here.

The Bulli seam, the most important of those worked in the Illawarra coal field of New South Wales, consists of high grade bituminous coal. It is about 6 feet thick on the average. It forms the top member of the Permo-Carboniferous system in this district and is overlain, with slight disconformity, by the basal beds of the Triassic system (Hawkesbury system) which is of fresh-water origin. Owing to contemporaneous erosion, the Bulli seam has suffered in some places,

[1] Manuscript received, April 26, 1933.

[2] Department of Home Affairs.

[3] *Arkansas Geol. Survey Bull. 3* (Little Rock, 1930).

[4] W. G. Woolnough, "Stone Rolls in the Bulli Coal Seam of New South Wales," *Jour. and Proc. Royal Soc. New South Wales* (1910), pp. xliv, 334-40.

and is reduced in thickness or even completely eroded. For the most part, however, it maintains fair uniformity of dimensions throughout the district.

The rocks of the New South Wales coal basin form a broad geosyncline having its center at Sydney, with very gentle dips in all directions. In the Illawarra coal field the coal measures rise from beneath sea-level at a point about 30 miles south of Sydney, and form a precipitous coast line with a narrow coastal plain for another 50 miles, where they attain an altitude of about 2,000 feet a few miles inland. The coal, principally the Bulli seam, has been extensively worked, by shafts where it is below sea-level, and by adits all along the coastal escarpment where it rises above sea-level.

The floor of the Bulli seam consists of dense shale, normally about 12 feet thick, separating the Bulli seam from the underlying "Four-Foot seam." Almost everywhere the roof of the Bulli seam is shale of varying thickness. Locally, owing to contemporaneous erosion, this shale is removed, and the roof is formed of the basal sandstone of the Hawkesbury series, which is porous in character and somewhat friable. In places, as already noted, the whole or part of the Bulli seam has been removed by contemporaneous erosion.

In places where there is a shale roof the coal is quite normal, but where there is a sandstone roof, the coal is nearly or quite pinched out, at intervals, by fold-like risings of the floor shale. These constitute what are known to the miners as "stone rolls."[5] Such rolls appear to be confined to those areas where the cover of the Hawkesbury series is not very thick, and they are not met with in the deeper workings farther north. They consist of local thickenings of the floor shale of the Bulli seam, but the disturbance is confined to that bed, and the underlying Four-Foot seam is not affected in any way.

In most places the coal is thinned over the crest of a roll, and a partial compensation is provided by thickening of the coal on both sides, like a layer of dough which has been rolled out in the middle. The compensation is not complete. The coal over the crest of the roll is markedly compressed and hardened, causing a noteworthy increase in specific gravity.

In most places the roll occupies only part of the thickness of the seam, the coal passing over the top of it. In such conditions the roof of the seam is not affected at all. In extreme cases the roll is of larger dimensions and extends from floor to roof, and even a few inches into

[5] The rolls occur chiefly where the covering of roof shale has been removed. The swelling effect extends, however, slightly farther, and is met with under a thin capping of residual shale close to the borders of a denuded area. This is the case with the big roll illustrated in Figure 1.

the roof. Figure 1 indicates to scale the structure of the largest roll examined by the writer.

The floor shales involved in the rolls show strong evidence of compression in the form of many slickensides and incipient jointing.

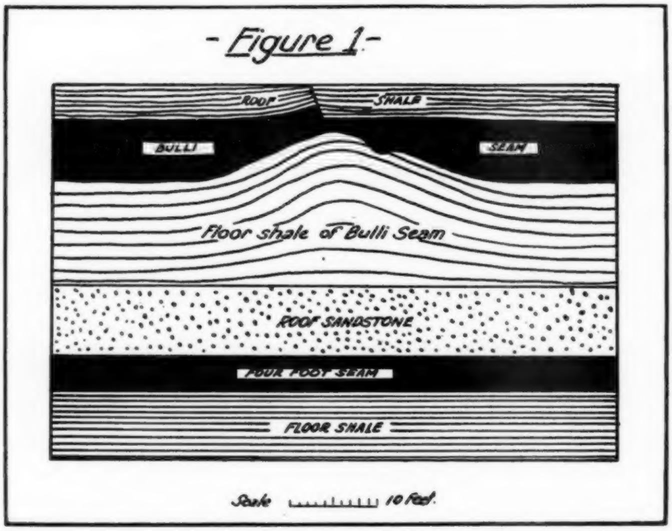

FIG. 1.—Diagram showing structure of a "stone roll." "Rolls" occur in Bulli seam where roof shale has been removed by contemporaneous erosion, or in immediate vicinity of such places. Swelling of floor shale gives rise to compression of coal, causing hardening, increase in specific gravity, lowering of volatile hydrocarbon content, jointing, and, in extreme cases, faulting and displacement of seam to small extent.

All of the phenomena connected with these rolls seem to suggest strong local compression. Naturally the first explanation which springs to the mind is that the rolls are mere local foldings of the coal and its associated strata due to regional compression of a mild character. That this is not so is shown by the fact that all of the effects are confined to two horizons only, the Bulli seam and its floor shale; while the underlying Four-Foot seam and the roof sandstones are not disturbed except in the case of the latter immediately over one or two of the largest rolls. Further, the whole of this part of New South Wales gives undoubted proof that it has never been subjected to compression since the middle of Paleozoic time. Everything in the geology and physiography of the region points to epeirogenic movement and tensional stress.

The explanation offered by the writer is that the floor shales of the Bulli seam are of such a composition as to be capable of hydration, oxidation, or carbonation, or a combination of these effects. In places where they are protected by the preservation of the original roof shale of the Bulli seam from direct accession of carbonated and oxidizing meteoric waters, they show no traces of increase of volume. Where, on the other hand, contemporaneous erosion has removed this protection, and the roof of the seam consists of a relatively small thickness of porous sandstone, meteoric water has percolated through the coal, and has caused marked increase in bulk of the floor shale. While the effect was certainly more or less uniform in considerable areas, it is only to be expected that the yielding to the stress would be localized along lines of weakness. In fact, the rolls tend to develop *en échelon* as long narrow domes.

The writer does not claim originality in regard to the theory of expansion folding due to oxidation, hydration, and carbonation of shaly beds. This explanation was given by Professor Sir Edgeworth David to his students many years ago, in description of very similar phenomena which are extensively exhibited in the railway cuttings near Sydney in the Wianamatta shales, the top member of the fresh-water Hawkesbury system, of Triassic age. The shales are fine-grained, carbonaceous muddy sediments with notable amounts of pyrite and barite. Their original iron compounds are largely in the ferrous condition. Where exposed in artificial excavations (they are very extensively used for brick making), large compression features are developed in them. The descriptions given by Croneis[6] might have been written about these expansion folds and faults in the Wianamatta shale. Downward, the folding passes into less and less acute anticlines, until it disappears. Upward, in the more weathered material immediately underlying the subsoil, it becomes more and more acute, first forming sharp anticlines which become more and more overfolded, until fracture supervenes and the folds pass into overthrust faults. In the Wianamatta shales these effects are directly associated with the weathering of the shales, and with the deposition of limonite on a considerable scale. Such definite evidences of oxidation are not visible in the stone rolls at Bulli, and in that case the dynamic effect is probably to be attributed to hydration of more or less bentonitic constituents of the floor shale.

Still other examples possessing features of some interest have come to the writer's notice in Queensland and New Guinea during the last few years in connection with the search for oil in Australia.

[6] *Op. cit.*, p. 336 and Pl. 41A.

At Longreach, in central Queensland (Lat. 23° S., Long. 144° E., approximately) natural paraffine, liquid at the temperature of the artesian water with which it is associated, has been known for some years in artesian wells which supply the town of Longreach with water. Consequently, there has been considerable activity in oil prospecting in the district, and serious efforts have been made to carry out detailed geological mapping of the area, in order to locate any structures favorable for oil occurrence. After more than two years' work, the results of this mapping remained paradoxical and unsatisfactory, and it is only recently that a partial explanation has been forthcoming.

The surface formations of the district are marine beds of Cretaceous age showing undoubted evidence of deposition in very shallow water, near land, and with abrupt variation in conditions of environment. Individual beds are sharply lenticular, and exhibit rapid lateral variation. Marine shells are extraordinarily abundant in patches, while, on the same horizon, and within a few yards, one encounters equally prolific plant remains, and in some places pseudomorphs of limonite after halite. Some of the salt crystals form little clusters round the casts of plant stems, showing that salt water was evaporated in marshy pools occupied by vegetation standing in its original position of growth.

Below the zone of weathering the Cretaceous beds are fine sandstones and shales, somewhat calcareous and markedly glauconitic, some of the glauconite being apparently detrital. At the surface the rocks are completely oxidized and are yellowish in color. The area is one of very low relief, and is subject to very high summer temperatures and to long periods of drought. Superficially it is similar to much of the country in West Texas and New Mexico. Even the largest streams are intermittent, their normal condition being that of a chain of pools, though there is usually a slow drainage through the sands and gravels of the "river" beds. Smaller streams carry water only after rain. In drought periods they dry up completely, for 2 or 3 years at a time in specially severe seasons, such as have prevailed in recent years.

Weathering is deep and complete, and rock outcrops are few and far between. Nevertheless, in the earlier stages of the work, it was thought that there were sufficient recognizable "outcrops," the "dips" of which could be determined, to make it possible to complete the geological map, and to determine the structures of the region. It was not long before it was found that such mapping of dips and outcrops produced a maze of indications which were utterly incomprehensible

and mutually inconsistent. The field workers conscientiously recorded the "outcrops" which they had succeeded in tracing, and showed that they *intersected* one another. When the impossibility of such a structure was indicated to them by senior consultants they stoutly maintained, and ultimately proved, the correctness of their delineation of the "outcrops." This being so, it became obvious that the fallacy lay, not in the intersection of the lines, but in the idea that they represented true "outcrops." Such "pseudo-outcrops" could be followed continuously for distances of hundreds of yards, possessing apparently all the characteristics of normal rock exposures. Pits sunk a few yards back from the "outcrop" failed to reveal anything with the same lithological characters, and it was obvious that the solidity of the "outcrops" was merely superficial.

It required much detailed investigation before it was discovered that we were faced here with the phenomenon of development of *concretions* on an enormous scale. The writer has not yet come across any description, in geological literature, of concretionary structures with diameters of at least 200 yards, and probably of as much as $\frac{1}{4}$ mile, but such these structures were found to be. The explanation of the intersecting "outcrops" was forthcoming when a "nest" of such concretions, each of the order of about 10 yards in diameter, was found. In this case it was possible to trace individual shells of each of the component concretions into and through its neighbor. Here, there were several bands of hardening present in each concretion; whereas, in the giant forms, there was only one band in which hardening had occurred, simulating very closely a normal, slightly curved rock outcrop. Naturally, at points of intersection of individual concretions in the "nest," dip readings were extremely erratic, and many of the seemingly insoluble puzzles encountered in the earlier stages of the field work were explained.

This concretionary development does not exhaust the paradoxes in structure developed in this region. It was recognized early in the investigation that considerable swelling had occurred in the shaly members of the formation, and examples of the development of expansion folds and reversed faults on a small scale were met with, particularly in natural and artificial excavations. On account of the very slight relief of the surface, however, neither gullies nor railway cuttings are of sufficient size to exhibit the effects adequately. It was only by slow degrees that it became apparent that, in this expansion folding, there was present a major source of disturbance of the surface formations. Later it became evident that practically every slab of solid rock in the area had been tilted and disturbed. Even "out-

crops" occupying several acres were found to have been warped, cracked, and tilted. Careful comparison between recognizable outcrops and surface contours proved that no dips of more than a few degrees could possibly exist normally. Finally the conclusion was reached that, if an "outcrop" could be traced, or a "dip" read by means of a clinometer, it was safe to discard it and to regard it as an abnormality produced by superficial alteration associated with the processes of weathering.

It was found that measurable dips were almost entirely confined to stream channels, and that they could not be found on the low, intervening hills. This is taken to indicate that it is chiefly in the valleys, where the very inadequate water supplies are concentrated for the longest periods, that the forces of expansion have fullest play.

Though it does not form part of the argument of this particular contribution, it may be worthy of mention that it has been found possible to photograph very successfully from the air the slight soil and vegetational differences corresponding with rock structure, and that there is every hope that this method may eventually provide the solution of the complicated geological problem of the Longreach area. It seems possible that the "warts and pimples" produced on the "outcrops" by the concretions and expansion folds can be recognized in the photographs, smoothed out and neglected, and that application of the methods of contour-outcrop mapping may then be applied in an intelligible fashion.

A somewhat different set of conditions is encountered in Papua, and probably also in New Guinea. These are summarized in Wyllie's resumé of the geology of these two territories. Long continued and detailed geological surveys were carried out in these two territories on behalf of the Australian Government by the Anglo-Persian Oil Company. The results are published in a voluminous work[7] in which full details are given. These are summarized admirably by B. K. N. Wyllie in his critical review, which forms the seventh part of the work in question. He figures, diagrammatically, a typical anticline like the one which has been extensively drilled at Popo, by the Anglo-Persian Oil Company on behalf of the Australian Government, unfortunately without success. He shows that the apparent extreme complication of some of the anticlinal structures is to be attributed to plastic movements in the more argillaceous members of the formations participating in the architecture of the region.

[7] *The Oil Exploration Work in Papua and New Guinea.* Conducted by the Anglo-Persian Oil Company, on behalf of the Commonwealth of Australia (1920-1929). Edited by B. K. N. Wyllie.

The writer would go further. Though he can not claim to have made observations comparable in extent with those of the Anglo-Persian geologists, personal experience in Papua suggests that at least some of the movement can be attributed to exaggeration of the phenomena which form the subject of this paper.

All the drilling operations in search for oil in Papua have been failures for mechanical reasons. Interbedded with the marly and sandy beds which form the bulk of the Tertiary formations, among which abundant indications of oil have been encountered, are beds of bentonitic character. Solid under normal conditions, these become fluid when the drilling water reaches them. The material swells enormously, and introduces all kinds of complications. In some places it has forced its way through the casing to the surface and has produced great accumulations of mud there. At Hohoro, on Vailala River, underground movements were caused of such severity as to rupture the 12-inch casing as if it had been cut in a shearing machine. It is obvious that, under any conditions in which water can obtain access to these bentonitic beds, enormous compressive stresses are developed.

Recognition of this fact explains much that is obscure in the geology of the Gulf Division of Papua. Physiographically, the contours are dominated by landslip topography. Geologically, as pointed out by Wyllie, there are apparently major anticlines and synclines, of considerable size and sharply folded. The outer limbs of these structures can be delineated quite satisfactorily. The crests of the anticlines, however, do not behave normally, and present the structure of a crazy quilt, small blocks of harder rock material lying at all kinds of angles, making it impossible to draw a reasonable looking section.

A possible explanation of this set of conditions was observed by the writer at Popo, Papua. A minor stream, during torrential rain, had eroded its bed rapidly, and had cut through an impervious layer of marl, reaching the subjacent bentonitic layer, which had previously been protected from access of water. The bentonitic material had become liquefied, and had been extruded as a veritable mud torrent, which had flowed down the hill carrying débris, including large trees, with it. Even from a little distance the collapse of the surrounding areas of more solid rock formation was clearly visible. When, after a few years, the tropical forest shall have again asserted itself, and have hidden the scars of this sudden eruption, the geologist, limited in his movements by the tangle of vegetation, may measure a series of widely divergent dips on the broken and disturbed rock masses, and may easily obtain an idea of complication of structure entirely inaccurate, and actually misleading.

Similar results appear from the work of a geologist employed by a private company in Papua. The complete shattering and displacement of the crest of a major anticline, with development of "crazy" structure, is directly attributable to the expansion of the bentonitic members of the formation when they became exposed to the action of meteoric waters by the process of erosion.

Geological literature relating to oil fields, for instance those of Trinidad and Roumania, strongly suggests that similar effects are to be met with there, and that the masking effects of pseudo-compression have not been given, perhaps, all the weight they should possess. In consequence, attempts have been made to build up the elements of the "crazy" pattern into structures supposedly produced by normal compression forces. The result has been, in Papua, to produce a false impression of structure, and to lead to costly and fruitless drilling operations, and similar mistakes may have been made in other fields.

The question also arises whether some of the structures in Arkansas[8] may not be found to be due to development of pseudo-compression structures, on a scale hitherto regarded as impossible, rather than to the production of normal folds by means of uniform regional stress.

SUMMARY

1. All bentonitic formations and many shaly structures are capable of undergoing great increase in volume as a result of hydration, oxidation, and carbonation when exposed to the action of meteoric waters.

2. In many areas where stratified formations are either entirely undisturbed, or are in a general condition of tension, such local expansions produce effects, including folding, overfolding, reversed faulting, and development of slickensides, normally attributable to regional compression.

3. In regions of poor geological exposure such local effects assume a false appearance of major importance and may create wrong impressions as to the nature of the folding forces affecting the area.

4. In Papua, where regional compression has produced major fold structures, the crests of the anticlinal structures have been shattered and displaced by the expansion of bentonitic members of the series, and the entirely false impressions with regard to the details of the structures have been produced.

5. In central Queensland, concretionary action on a gigantic scale and involving increase in bulk of some of the individual beds, has produced pseudo-dips which are most confusing. The interference of adjacent concretions has developed hard bands crossing one another, giving the appearance of intersecting outcrops, the whole producing a picture which is entirely misleading, and which has given rise to false interpretations of geological structure.

[8] Carey Croneis, *op. cit.*

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STUDIES IN PALEOGEOLOGY[1]

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ABSTRACT

Paleogeology is defined as the science of the geology of ancient time. Paleogeologic maps are presented which show the areal geology and the regional structure of the region of the United States at the beginning of Mississippian time; in early Pennsylvanian time; and at the beginning of Cretaceous (Comanche) time. Similar maps may be prepared of other surfaces exposed during geologic time and they may be compiled for other countries. These maps have a wide application and give a different picture of geologic history.

Oil and gas are found as high in their containing reservoir as it is possible for them to move. If true of the present, it must have been true in the past and a study of the changing areal and structural geology during geologic time becomes of prime importance. The earliest, therefore the most important, trap to form in many American petroleum provinces was a reservoir rock which was wedged out and overlapped by an impervious cap rock. Paleogeologic maps offer a means of locating these wedge edges and their application to petroleum geology opens a different approach to the problem of finding petroleum reserves.

Introduction

Paleogeology is defined as the science of the geology of ancient time. Paleogeology differs from paleogeography in the same manner that geology differs from geography.

Paleogeologic maps show the areal geology of an ancient surface. They are constructed by plotting the formations which are found in contact with the base of the key or datum horizon, and as the control becomes sufficient, the geologic contacts and formation boundaries may be drawn. Through interpretation of the relations of the older to the younger rocks, the structure of the rocks may be determined in the same manner as the present structure is interpreted from areal geologic maps. The extent of the shore lines, overlaps, and regional warping and truncation are readily determined. Through the use of isopachous maps in conjunction with the paleogeologic maps, the topography and relief of the ancient surface may be ascertained. Each unconformity surface offers an opportunity for making a paleogeologic map and the greater the overlap of the overlying key formation, the

[1] Read before the Association at the Houston meeting, March 23, 1933. Manuscript received, June 26, 1933. Read before XVI International Geological Congress, Washington, D. C., July 24, 1933.

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more interesting and more valuable the story revealed by the paleogeologic map.

The unconformity surfaces in the United States which offer the best opportunities for the construction of paleogeologic maps are those of the greatest regional extent and those in which the involved formations have been widely determined and where there is more cr less agreement as to their age relations. Those unconformity surfaces in the United States which have been mapped by the writer and are presented as type paleogeologic maps in this article are the pre-Mississippian, pre-Pennsylvanian, and pre-Cretaceous (Comanche). The methods here used are adaptable to many other unconformity surfaces and to many other countries.

Pre-Mississippian Paleogeology

A paleogeologic map of the area of the United States at the beginning of Mississippian time is shown in Figure 1. This map represents the areal geology of the surface upon which the Mississippian sediments were deposited. It was prepared by plotting, with different symbols, the age of the different rocks which are found in contact with the base of the Mississippian, and as the data accumulated and the control increased, formation boundaries were drawn with increasing accuracy. Only those points of control were used of which the formation in contact with the base of the Mississippian was known, excepting the Devonian system, which obviously was present, and not removed by erosion, prior to the overlap by the Mississippian rocks.

The compilation of such widely scattered information, based on the work of many geologists, involves entering into many stratigraphic controversies. The writer has accepted in the preparation of the pre-Mississippian map, for example, the opinion of those geologists who consider the Chattanooga shale to be basal Mississippian rather than late Devonian in age. For those parts of the United States, therefore, where the Chattanooga shale is present, the map may be considered as a pre-Chattanooga paleogeologic map, and for most of the other parts of the country, a pre-Madison limestone map.

The distribution of the rocks as shown on the pre-Mississippian paleogeologic map furnishes a clue to the regional structure of the area of the United States at that time. Thus, a structurally high axis is shown as extending from Utah and Wyoming southeastward across the country and through the Central Kansas uplift; the Ozark uplift in Missouri; the Tennessee or Nashville dome; and opening toward the southeast beyond the present Appalachian Mountains in Tennes-

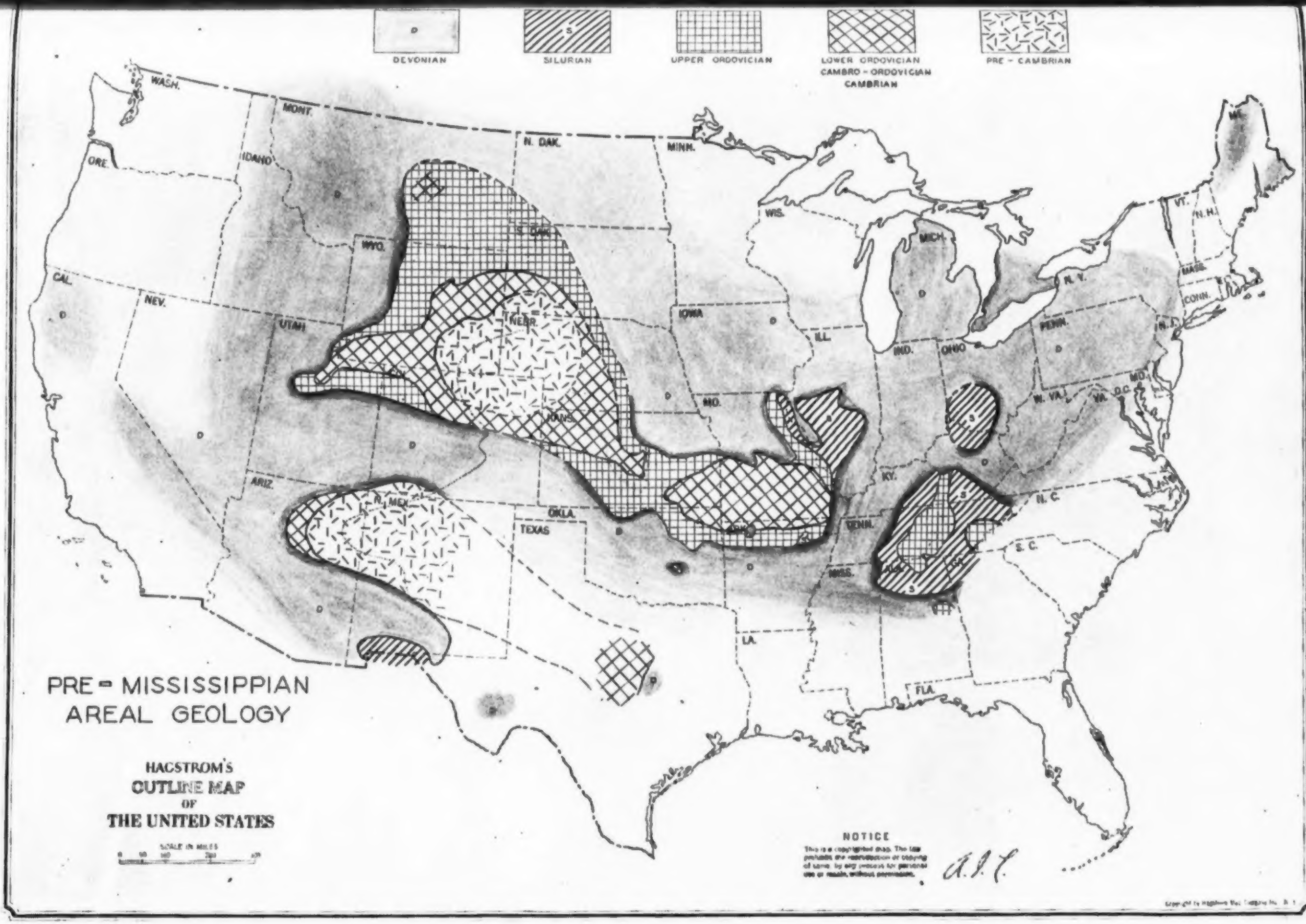

FIG. 1.—Paleogeologic map of United States at beginning of Mississippian time, representing areal geology of surface upon which Mississippian sediments were deposited. Areas in blank are where information is lacking.

see. There is some evidence that a parallel high area extended from the Grand Canyon region of Arizona across New Mexico and at least as far as the central part of Texas. This early northwest-southeast trend of the folding probably influenced the direction of some of the later folding such as the Amarillo-Arbuckle trend in Texas and Oklahoma. A study of the map shows the Devonian rocks overlapping the arch at many places, thus indicating that the arch was present at least prior to Devonian time and that it persisted as an arch until overlapped completely by the Mississippian Chattanooga shale and Madison limestone. Additional paleogeologic maps of the unconformable surfaces within the Devonian and Silurian systems will be necessary to determine more accurately the age of these major structural trends.

Pre-Pennsylvanian Paleogeology

A paleogeologic map of the area of the United States at the beginning of, or early in, Pennsylvanian time is shown in Figure 2. This map represents the areal geology of the unconformity surface upon which the Pennsylvanian sediments were deposited and is nearly the same map as that published by the writer in 1931.[3] It is shown again to complete the series and to show the change in conditions since pre-Mississippian time. This map, like the pre-Mississippian map (Fig. 1) was compiled from many sources and involves a decision in many controversial points, of which one of the most important is the age of the Stanley shale and Jackfork sandstone in the Ouachita Mountains of Oklahoma and Arkansas. The writer has accepted the opinion of those geologists who believe the Stanley shale is Upper Mississippian in age and the Jackfork sandstone is Pottsville in age.

By interpreting the areal distribution of the pre-Pennsylvanian rocks in terms of structure, it is seen that the regional structure of the area of the United States is quite different from the structure in pre-Mississippian time. The pre-Pennsylvanian structure consists chiefly of the southwest pitching arch extending from New Mexico northeastward into Minnesota and Canada and several lesser folds and uplifts such as the Nemaha ridge extending across Kansas, the La Salle anticline in Illinois, the northwest-southeast folding across the Ozark region of Missouri, and many minor folds and faults now known through drilling for oil and gas in the Mid-Continent states.

Across the upturned, eroded, and truncated edges of the pre-Pennsylvanian formations, the Pennsylvanian sediments were deposited. Paleogeology suggests that most of this erosion and removal of the

[3] A. I. Levorsen, "Pennsylvanian Overlap in United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 2 (February, 1931), Pl. I, opp. p. 142.

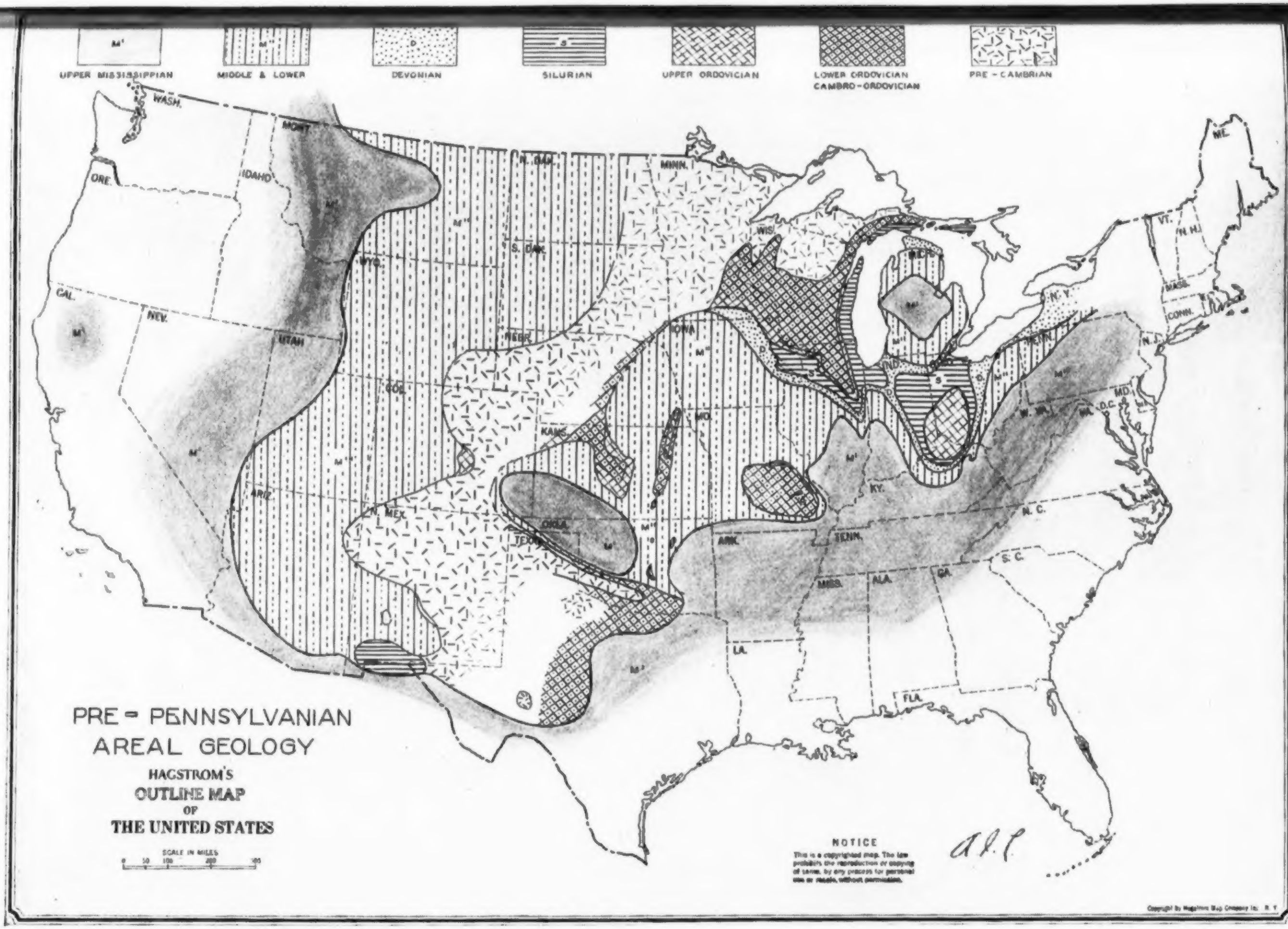

FIG. 2.—Paleogeologic map of United States at beginning of, or early in, Pennsylvanian time, representing areal geology of surface upon which sediments of Pennsylvanian age were deposited. Blank areas are areas of no information. of surface upon which Cretaceous sediments were deposited. Cretaceous shown only in part.

material occurred between Chester and Pottsville, and that the pre-Pennsylvanian contacts shown in Figure 2 do not represent shore lines or margins of deposition, but are the eroded edges of formations which may have originally extended far beyond their present limits. This interpretation marks one of the chief differences between paleogeology and paleogeography.

Pre-Cretaceous (Comanche) Paleogeology

The paleogeologic map of the area of the United States at the beginning of Lower Cretaceous or Comanche time is shown in Figure 3. This map represents the areal geology of the unconformity surface upon which the sediments of the Cretaceous system were deposited. It was prepared in a manner similar to that used in the preparation of the other maps in that all of the rocks found in contact with the base of the Cretaceous system were plotted with appropriate symbols, and as the information became sufficient, system contacts were drawn. Some of the data are from subsurface information, but most are recorded in the geologic literature. As in the preparation of the other maps, divergent opinions about correlations were encountered. The chief variation was about the basal Cretaceous (Comanche) formation. The writer adopted the opinion of those geologists who consider the Morrison formation as Comanche rather than Jurassic in age, and the map of large areas in the Rocky Mountain states might be considered as a pre-Morrison paleogeologic map. Another more recent difference of opinion bearing on the construction of this map is the age of the Whitehorse sandstone and younger formations of the so-called Permian system. The writer has, for the present, adopted the early correlation of these formations as Permian in age rather than the recent correlation by Roth,[4] who believes that they properly belong to the Triassic system.

The pre-Cretaceous paleogeologic map shows the Cretaceous system as progressively overlapping the Jurassic, Triassic, Permian, Pennsylvanian, and finally the older Paleozoic and pre-Cambrian rocks from west to east or from the Rocky Mountain states to the central states. This progressive eastward overlap of the Cretaceous system upon the rocks of each of the older systems seems to fix the time of the origin of the Prairie Plains homocline or the major regional westward dip of the pre-Cretaceous rocks of the west-central states as having occurred between Jurassic and Cretaceous time.

[4] Robert Roth, "Evidence Indicating the Limits of Triassic in Kansas, Oklahoma, and Texas," *Jour. Geol.*, Vol. 40 (November–December, 1932), pp. 688–725.

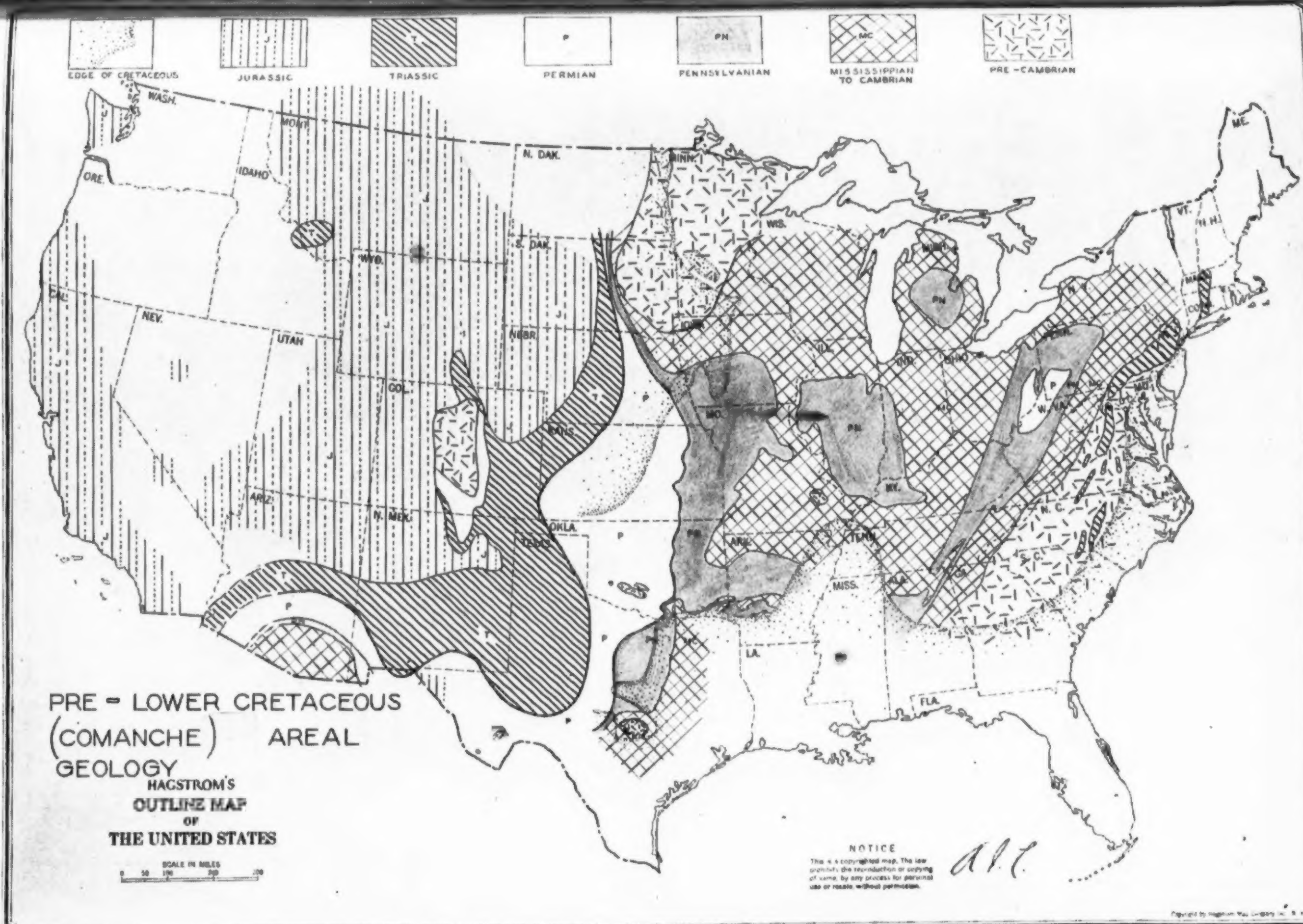

FIG. 3.—Paleogeologic map of United States at beginning of Lower Cretaceous or Comanche time, representing areal geology of surface upon which Cretaceous sediments were deposited. Cretaceous shown only in part.

As shown by the pre-Cretaceous paleogeologic map, the regional structure of the area of the United States prior to the transgressive overlap by the Cretaceous system seems to have been a broad, low, south pitching arch, the axis of which extended from the Great Lakes region southward beyond Louisiana including approximately the area of the Mississippi River valley. The west flank of this arch consisted of the Prairie Plains homocline striking south from Minnesota to central Texas and dipping westward excepting where interrupted by uplifts as the Sioux area of Minnesota, Iowa, and the Dakotas; the "Ancestral Rockies" of Colorado; and the Arizona-Sonora uplift in the southwest. The western margin of this west flank is concealed in the covered area of Idaho and Nevada, but as the Jurassic is also found along the Pacific coast, it may have extended as far west as that region. The east flank of this arch is found in the east-southeast dip of the rocks along the Appalachian mountain region of the eastern states. This east dip is now modified by many thrust faults. If these faults are eliminated and the structure reconstructed to pre-fault time, the result appears to be a profound southeast dip extending from New York to Alabama. The main features of this up-warping are better observed if we eliminate those folds, as the Michigan basin, the Cincinnati, Nashville, and Ozark domes, and the La Salle and Nemaha anticlines, which were formed prior to the Jurassic-Comanche interim. The projected intersection of the two limbs of the pre-Comanche arch is at some point near the west side of the Gulf of Mexico. The movement which resulted in this arch probably continued into Cretaceous time as the Upper Cretaceous formations overlap the older in the embayment area of Arkansas and Mississippi. The Prairie Plains homocline, which has been an important factor in the work of the Mid-Continent geologists, is thus seen as part of the west limb of a regional arch formed in the interval between the Jurassic and Comanche periods.

Comparison of Regional Structure

The main structural features of the three paleogeologic maps are shown in Figure 4. The pre-Mississippian axes extend southeast from Utah and Wyoming to Tennessee and from Arizona to Texas; the pre-Pennsylvanian axis extends southwest from Minnesota to New Mexico; and the pre-Cretaceous axis extends southward from the Great Lakes region toward the Gulf of Mexico. It is apparent that the regional folding of each period is almost entirely independent of the folding of the preceding period, both as to direction and location. If to this comparison is added the post-Cretaceous folding which has

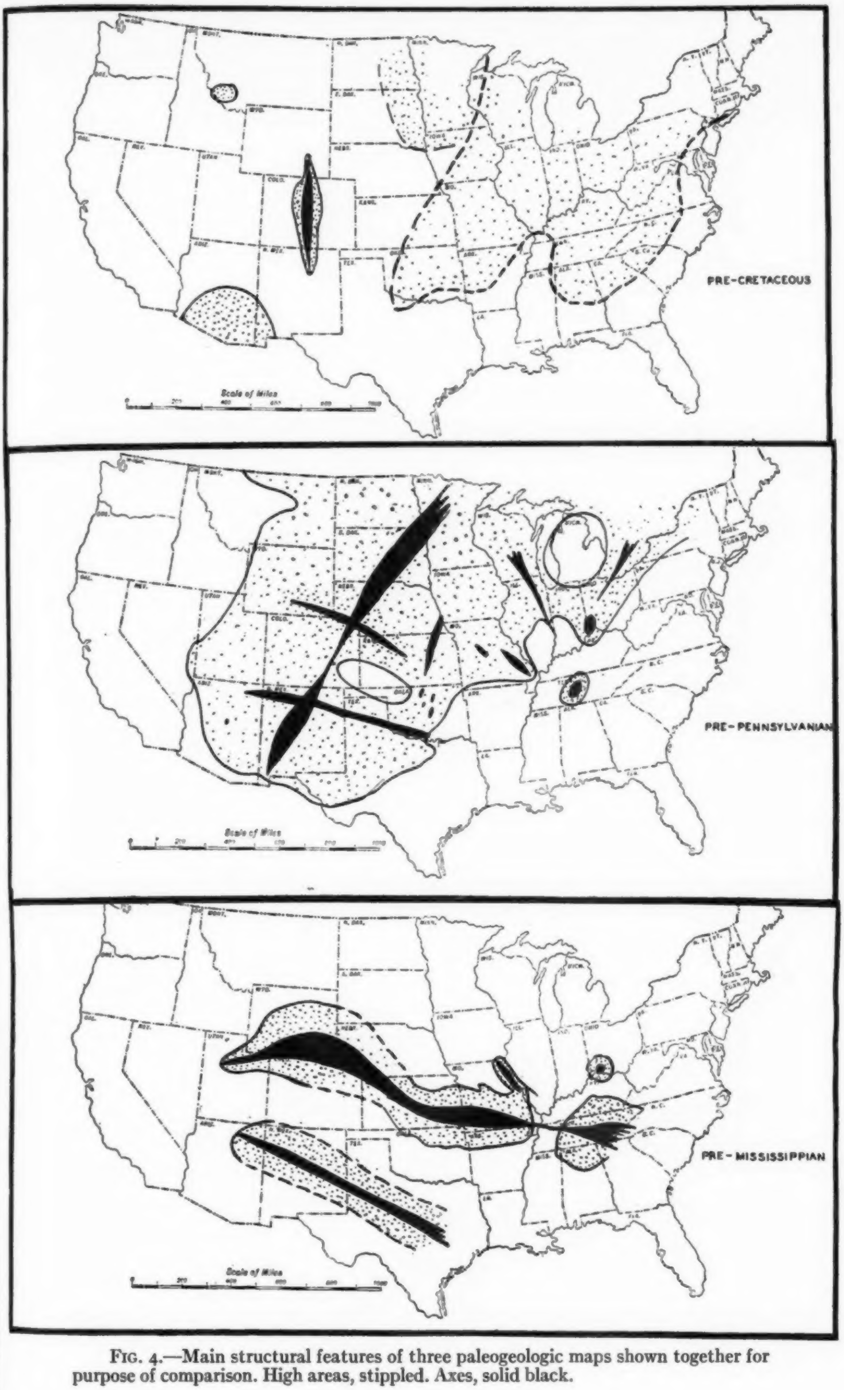

FIG. 4.—Main structural features of three paleogeologic maps shown together for purpose of comparison. High areas, stippled. Axes, solid black.

been concentrated in the mountainous western states, the non-conformity of position and direction of folding is still further brought out.

Applications of Paleogeology to Petroleum Geology

The anticlinal theory of the accumulation of oil and gas is generally understood to mean the gravity separation of gas, oil, and water within the reservoir rock. Thus, in a water-saturated reservoir rock, gas and oil which are added will tend to arrange themselves into layers in the order of their specific gravities, the lightest rising the highest. Ley[5] has suggested the term "up-dip accumulation" rather than "anticlinal accumulation" inasmuch as many oil and gas pools are not closely associated with anticlines within the ordinary meaning of the term but all are found as far up the dip of the reservoir rock as the gas and oil can move.

Investigations of oil and gas pools throughout the world have shown that the oil and water, or the gas and water, contacts tend to approach a level plane. Accumulations of oil and gas, in other words, are found to approach complete gravity adjustment to the present structure and attitude of the reservoir rock regardless of its age or geologic history. Furthermore, the oil and gas are everywhere found to occupy the highest possible position within the containing reservoir rock. As these phenomena are true of our present oil and gas pools, they must have been true of the oil and gas pools of the geologic past and a study of the changing attitude and structure of the reservoir rock, after the oil and gas have entered it, becomes of primary importance.

Study of the geologic history of many oil and gas pools shows that the present attitude of the reservoir rock is not the same as in the past, but that it is the result of many periods of folding, tilting, uplift, erosion, and overlap of both local and regional extent. It may be assumed that the adjustment of the oil and gas to the present structure is likewise the result of a combination of repeated adjustments and migrations, each of which brought the oil and gas into gravity adjustment with the changing attitude and structure of the reservoir rock. This adjusting process must have commenced as soon as the oil and gas entered the reservoir rock and continued to the present. It must have continued through varying environments of depth, load, pressure, temperature, and water concentration, all of which probably had a bearing on the speed and ease with which the process advanced. Stated differently, oil and gas pools in Ordovician rocks at the end of Ordovician time, for example, were formed and retained under the

[5] Henry A. Ley, oral communication.

same principles of up-dip accumulation and gravity adjustment which we believe operate to-day, but as applied to the structural condition of that time. These pools were in a different structural environment during Mississippian time, again during Pennsylvanian time, and again during Mesozoic time, but adjustment must have continued to operate with a consequent shifting and migration of the oil and gas into higher and higher parts of the reservoir rock as they became accessible.

If our reasoning about the repeated migration of oil and gas in order to maintain their position in harmony with the structure of the reservoir rock is correct, the earliest trap to form in the reservoir rock after the oil and gas have entered it becomes very important. The first segregation of oil and gas will be in the first trap available and the influence of this early trap and accumulation will be felt throughout the geologic history of the pool. When the early trap is of regional proportions, a petroleum province may be the result and if it be of strong and definite "trapping ability," the early accumulation may withstand all subsequent changes in the attitude of the reservoir rock and become the final site of the pool. The importance of ascertaining the location and types of early traps in the reservoir rock can scarcely be overemphasized in any attempt to trace the geologic history of an oil or gas pool.

At many times during geologic history the earliest trap to form consisted chiefly of a porous reservoir rock wedging or lensing out up the dip and overlain by a relatively impervious cap rock. Many miles of such wedge edges are shown in the paleogeologic maps (Figs. 1, 2, and 3).

SEQUENCE OF EVENTS

A geologic sequence which seems to have been operative in many oil and gas fields is shown in Figure 5. The sequence is as follows.

1. The formation of a reservoir rock in which one side is marked by a thinning or wedging out. This side is wedge shaped and may be termed the "wedge edge." This wedging out may be of either local or regional magnitude. It may be of primary origin, due to the ordinary process of sedimentation such as lensing out of a sandstone, or more commonly, it may be of secondary origin, the result of tilting, uplift, erosion, and later overlap by an impervious cap rock. The important conditions are the shape and the fact that the wedge edge is ordinarily the high edge at the time it is formed.

2. As the wedge edge is the high edge of the reservoir rock any oil or gas which enters the reservoir rock will move into the high or

wedge end as far as possible. The question of the origin and source of the oil does not enter the wedge theory as it is sufficient to know that oil does originate and does at some time and in some manner enter the reservoir rock, and that as soon as it enters the reservoir rock it acts in accordance with the principles of up-dip accumulation and gravity

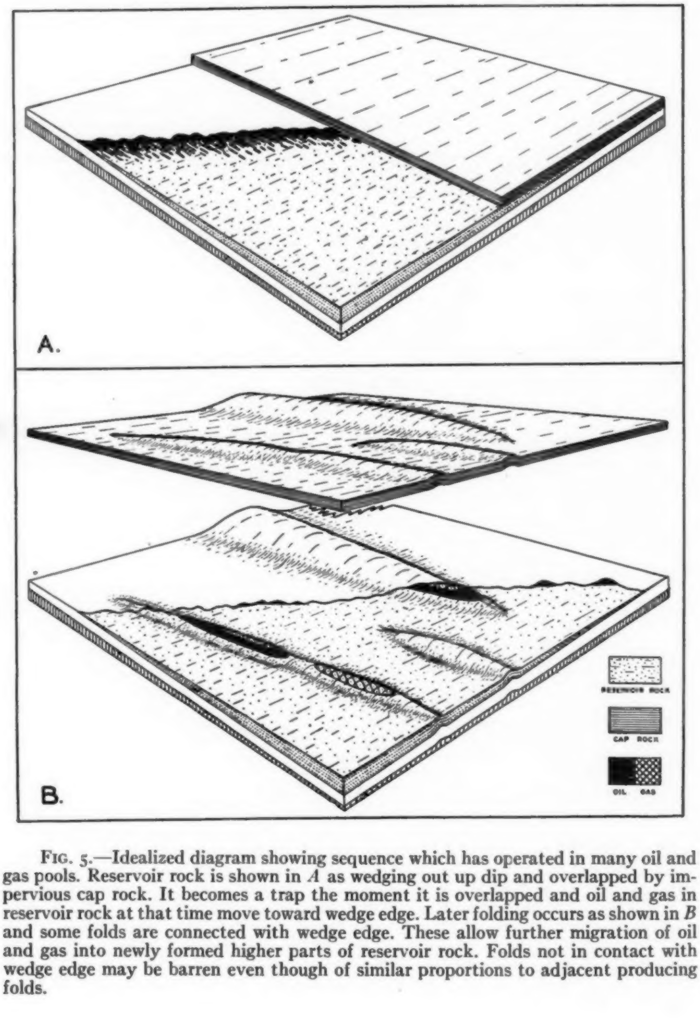

FIG. 5.—Idealized diagram showing sequence which has operated in many oil and gas pools. Reservoir rock is shown in *A* as wedging out up dip and overlapped by impervious cap rock. It becomes a trap the moment it is overlapped and oil and gas in reservoir rock at that time move toward wedge edge. Later folding occurs as shown in *B* and some folds are connected with wedge edge. These allow further migration of oil and gas into newly formed higher parts of reservoir rock. Folds not in contact with wedge edge may be barren even though of similar proportions to adjacent producing folds.

separation as expressed in the anticlinal theory. The wedge edge forms a barrier to the further advance of the oil and gas the moment it is overlapped and thereby furnishes favorable conditions in that the most advantageous trap for the accumulation of oil and gas is the one formed soon after the oil and gas enter the reservoir rock. Obviously the first trap to form after the oil and gas enter the reservoir rock is very important and the one which should be studied first because it is there that the primary localization of oil and gas occurs.

3. Later tilting, folding, faulting, and various other modifications of the attitude of the reservoir rock occur in the vicinity of the wedge edge and allow locally higher reservoir space to be accessible to the oil and gas which had previously accumulated in the wedge area. Thus, further localization of the oil and gas into these locally higher areas occurs,—everywhere, however, in conformity with the principle that they seek the highest possible level in the reservoir. These later modifications of the reservoir rock may continue through many periods of time and the oil and gas have been moved and adjusted to the structure many times since they first entered the reservoir rock. These continual and repeated adjustments may be the cause of some of the differences in gravity found in oils from the same reservoir rock, some of the variations in gas-oil ratios, and other variations in the physical characteristics of the oil and gas from the same reservoir.

Some of the later folds may be located in such a manner that they do not contact the wedge edge and consequently are barren of oil and gas even though they appear to be of a like magnitude and position to producing folds near by. In other words, the oil and gas had gone beyond the location of these folds before they were formed and the folding was not such as to permit a return into this location.

TILTING IN OKLAHOMA

The geologic history of Oklahoma furnishes a good example of the manner in which various uplifts and tiltings of the rocks may influence and control the accumulation and migration of oil and gas. Figure 6 shows by dip symbols the direction of four of the major regional tiltings of the rocks in Oklahoma as developed in the preparation of the paleogeologic maps shown in Figures 1, 2, and 3. Each of these homoclines caused a readjustment in the position of the oil and gas pools within the reservoir rocks involved in the folding, to the end that the final location of much of the oil and gas was reached only through complex processes.

A in Figure 6 shows the direction of the dip of the Devonian, Silurian, and Ordovician rocks at the time they were overlapped by

the Chattanooga shale. This south dip of these rocks is due to thickening in the Ordovician toward the south and to pre-Chattanooga uplift and truncation of the Ozark area on the north. The dip shown is based on isopachous maps between the Arbuckle limestone (Canadian) and the Fernvale limestone (Richmond) and between the Arbuckle limestone and the Chattanooga shale (Mississippian). The enlargement of these intervals toward the south and the overlap of the Chattanooga shale have been described by Weirich[6] and White.[7] Oil and gas in the reservoir rocks of the Devonian, Silurian, and Ordovician systems at the beginning of Chattanooga time must have moved northward and up the dip as far as possible.

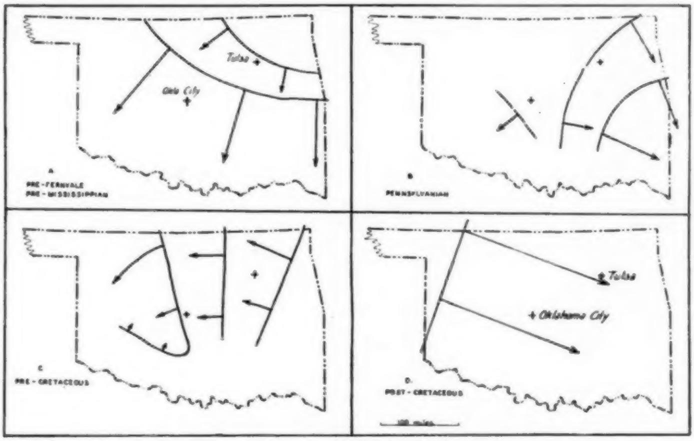

Fig. 6.—Direction of four major regional homoclinal tiltings of rocks in geologic history of Oklahoma as determined from paleogeologic maps.

B of Figure 6 shows the sinking of the southeastern part of the state during the deposition there of thousands of feet of Pennsylvanian shales, sands, and thin coals and limestones. The nature of this divergence of strata toward the southeast has been described by the writer.[8] The northwestward wedging out of Pennsylvanian sediments

[6] T. E. Weirich, "Simpson of Central Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), p. 1508.

[7] Luther H. White, "Subsurface Distribution and Correlation of the Pre-Chattanooga ("Wilcox" Sand) Series of Northeastern Oklahoma," *Oklahoma Geol. Survey Bull 40-B* (1926).

[8] A. I. Levorsen, "Convergence Studies in the Mid-Continent Region," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 11, No. 7 (July, 1927), pp. 657–82.

Idem, "Pennsylvanian Overlap in United States," *Bull. Amer. Assoc. Petrol. Geol.*. Vol. 15, No. 2 (February, 1931) pp. 113–48.

at a rate ranging from 50 to more than 250 feet per mile across eastern Oklahoma is due in part to a decrease in material westward but is chiefly due to repeated minor uplifts, truncations, and overlaps, all of which conspired to wedge out thousands of feet of geologic section. During Pennsylvanian time, then, the regional dip changed toward the southeast and any oil or gas in the Ordovician, Silurian, Devonian, Mississippian, and early Pennsylvanian rocks at that time tended to migrate up the dip toward the northwest. Notable local folding occurred during early Pennsylvanian time and was repeated at intervals throughout the Carboniferous. The local folds together with the wedged-out edges of the reservoir rocks trapped the oil and gas at that time. The direction of the movement of the oil and gas was completely changed from pre-Mississippian time and all of the oil pools in the pre-Pennsylvanian rocks must have been affected by the Pennsylvanian tilting.

C in Figure 6 shows the tilting downward toward the west which occurred between Lower Cretaceous (Comanche) and Jurassic time and involves all of the pre-Cretaceous rocks of Oklahoma (Fig. 3). This regional westward dip, known as the Prairie Plains homocline, varies between 40 and 75 feet per mile and, excepting where interrupted by the Oklahoma Mountains, extends from Nebraska and Iowa south to the Central Mineral region of Texas. This homocline is a complete reversal of the east-southeast dip developed during Pennsylvanian time shown in *C* and must have greatly modified all previous oil and gas accumulations. As with the other tiltings, there were local folds developed during this regional movement which further modified the structural pattern of the state.

D of Figure 6 shows the direction of post-Tertiary tilting in Oklahoma toward the southeast. This is in general due to the uplift of the Rocky Mountain region on the west and the resultant low regional southeast dips of the Tertiary formations in the Mid-Continent area. Though of low degree, probably averaging less than 15 feet per mile, its effect must have been felt because the present oil and gas pools in the area are in adjustment with the present sea-level.

OIL-FIELD EXAMPLES

Examples of oil- and gas-producing areas in which some of the principles developed in the study of paleogeology seem to apply are given in the following pages. The examples used are those of major producing areas or pools typical of a group or class of production. The importance of the early wedge shape in the reservoir rock and of the effect of the later changing attitude and structure of the reservoir

rock is clearly evident in many fields. The determination of these factors for any area may be considered as a typical study in paleogeology.

PENNSYLVANIAN SANDS IN OKLAHOMA

Figure 7 shows in idealized cross sections a change in the attitude of the Pennsylvanian rocks in eastern Oklahoma. The upper section shows the eastward dip which prevailed at the time the Permian

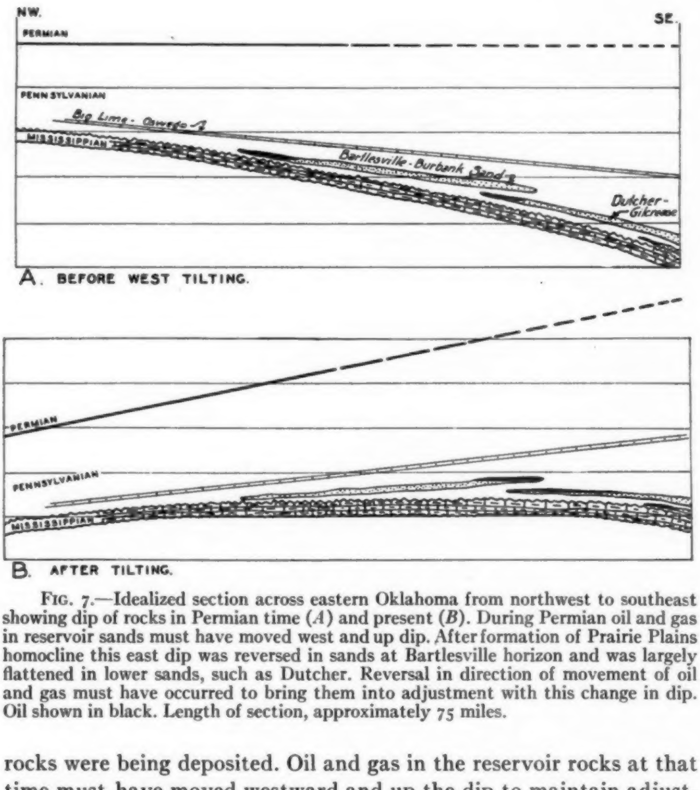

FIG. 7.—Idealized section across eastern Oklahoma from northwest to southeast showing dip of rocks in Permian time (*A*) and present (*B*). During Permian oil and gas in reservoir sands must have moved west and up dip. After formation of Prairie Plains homocline this east dip was reversed in sands at Bartlesville horizon and was largely flattened in lower sands, such as Dutcher. Reversal in direction of movement of oil and gas must have occurred to bring them into adjustment with this change in dip. Oil shown in black. Length of section, approximately 75 miles.

rocks were being deposited. Oil and gas in the reservoir rocks at that time must have moved westward and up the dip to maintain adjustment with the structure of the reservoir rock. *A* of Figure 7 corresponds with *B* of Figure 6. The structurally high parts of the reservoir rocks were along the west edge where the sands were wedged out and it was there that the early localization of the oil and gas occurred.

Later as shown in the lower section (*B*), the dip was reversed for the upper sands and those occurring at the Bartlesville sand horizon and was in places reversed but generally only flattened in the lower Booch and Dutcher sands. *B* of Figure 7 corresponds with *C* of Figure 6 and with the tilting shown in Figure 3. The effect of this reversed tilting was to reverse the direction of the oil and gas movement. The oil and gas in the Bartlesville sands then moved as far eastward as possible, and were finally trapped against the wedged-out eastern edge of the sand. The oil and gas in the Dutcher and Booch sands moved into local folds and traps in the vicinity of the earlier accumulation, but as the dip was not generally reversed, the oil and gas did not move far from the edge. Thus, in the area of Okmulgee and Creek counties, almost any sort of structural irregularity provided a trap for Dutcher sand oil, whereas farther east strong folds do not contain either oil or gas. The oil and gas had gone past the location of these eastern folds and later folding failed to provide higher reservoir space accessible to the early accumulation along the wedge area.

The southeast fringe of pools in Oklahoma is generally higher in gas content than are those located farther west. This may be due to the fact that the gas is more mobile and volatile than the oil and that in the later movements the gas moved farther out from the wedge edge and left the oil behind.

GREATER SEMINOLE DISTRICT

Most of the accumulation in the Seminole district, Oklahoma, is found in the Seminole or "First Wilcox" sand, of Ordovician age. The general conditions were described by the writer[9] when he had no conception of the importance, in fact the primary function, of the wedge shape of the Seminole sand.

The Seminole sand is found to wedge out up the dip and toward the southwest as shown in Figure 8. The wedging out is caused by an increase in dolomite and limestone and a decrease in sand grains toward the southwest to the approximate position of the edge shown in Figure 8, where the change from sandstone to dolomite is complete. The contours in Figure 8 are on top of the Viola limestone, which is found from 75 to 150 feet above the top of the producing Seminole sandstone. The contour interval is 500 feet. The pools producing from the Seminole sand are cross-hatched. The structure of the Seminole

[9] A. I. Levorsen, "Geology of Seminole County," *Oklahoma Geol. Survey Bull. 40-BB* (1928).

Idem, "Greater Seminole District, Seminole and Pottawatomie Counties, Oklahoma," *Structure of Typical American Oil Fields*, Vol. 2 (Amer. Assoc. Petrol. Geol., 1929), pp. 315–51.

district is, broadly, a northeast pitching arch locally modified by smaller domes, terraces, faults, and folds. Across this arch the Seminole sand (dotted) pinches out.

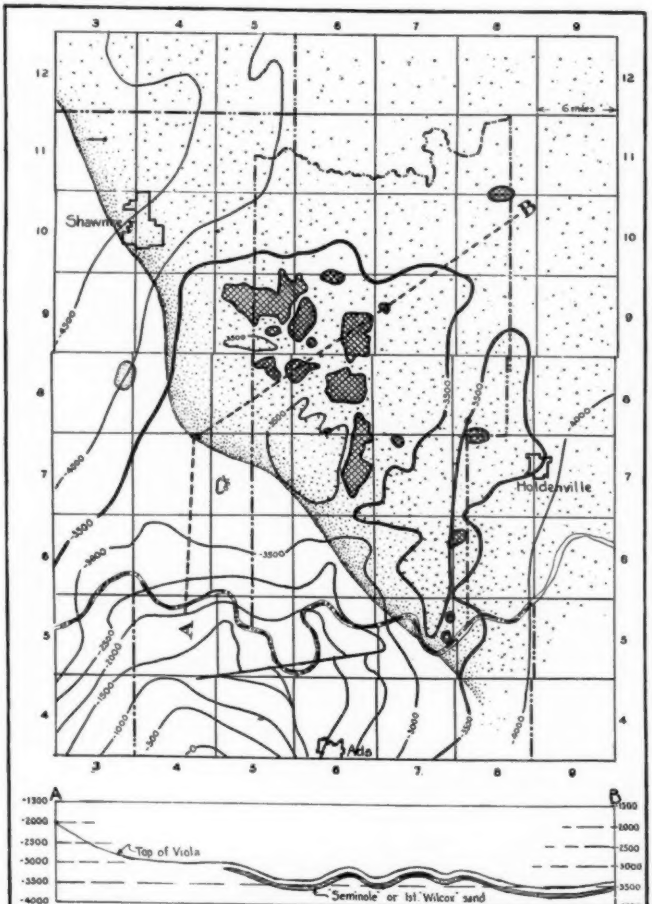

FIG. 8.—Greater Seminole district, Oklahoma, showing distribution of Seminole or "First Wilcox" sand (dotted) and oil pools producing from it (cross-hatched). Contour interval, 500 feet. Contours on top of Viola limestone (Ordovician).

The wedging out of the Seminole sand up the dip and across the northeast pitching arch is the fundamental and early cause of the ac-

cumulation of oil and gas in the Seminole district. The early localization was later modified by the local folding and tilting, and there were repeated migrations of oil and gas into higher parts of the structure as these became available during the succeeding periods of deposition, folding, erosion, and uplift.

Briefly, the successive events in the geologic history of the Greater Seminole district which bear on the accumulation of the oil and gas in the Seminole sand may be summarized as follows.

1. The development in late Ordovician time of the wedge shape in the Seminole sand.

2. The primary accumulation of oil and gas along, and in the vicinity of, this wedge edge, due to ordinary processes of gravity separation of oil, gas, and water probably began when the area was uplifted at the end of Devonian and before Mississippian time. The wedge edge of the Seminole sand crosses this early arch and pinches out up the dip (Fig. 1).

3. A sinking toward the east and southeast of the Seminole district and a lesser sinking toward the southwest left a broad arch extending from the Arbuckle Mountains northward through the Seminole district by middle Pennsylvanian time. The magnitude of this arch is shown in Figure 6*B* and is measured by the divergence both east and west of the Pennsylvanian formations. A further localization of oil and gas in the Seminole sand into the area of this arch occurred at this time.

4. Local, and in places sharp folds, accompanied by faulting, occurred at this time and permitted further localization of the oil and gas into pools in the Seminole sand. It was at this time that the Earlsboro, Seminole City, Bowlegs, Little River, Mission, and other pools were formed.

5. During the deposition of the Pennsylvanian there was repeated folding of the area as evidenced by local thinning of various formations over the early folds. Further migration of the oil and gas in the Seminole sand must have occurred at these times to maintain the gravity adjustment of the oil, gas, and water.

6. After Permian time, and probably between Jurassic and Comanche time, the entire area of Oklahoma, together with other parts of the Mid-Continent, was tilted down toward the west and the Seminole district became a part of the Prairie Plains homocline as shown in *C* of Figure 6. A further migration of the oil and gas must have occurred at this time to maintain the gravity adjustment during the time the regional dip of 50–75 feet per mile was being developed.

7. A reversal of the pre-Comanche dip has occurred since Tertiary

time and the tendency now is for a regional southeast dip to form, extending from the Rocky Mountains toward the Gulf of Mexico, as shown in *D* of Figure 6. Therefore the oil and gas in the Seminole district may even now be migrating to maintain adjustment with the present gulfward tilting of the region.

SUNSET-MIDWAY DISTRICT, CALIFORNIA

The map and sections (Fig. 9) of the Sunset-Midway field in California are adapted from the report by Pack.[10] The dotted area shows the distribution of the producing Etchegoin formation (Pliocene) which wedges out up the dip toward the southwest. The wedging out is due to transgressive westward overlap, the lower porous layers wedging out first and the upper parts later until finally the entire formation is overlapped and the overlying Paso Robles formation rests directly on the underlying Maricopa shale. Obviously the wedging out of the Etchegoin formation up the dip created a trap or barrier to the migration of oil and gas and occurred prior to the formation of the folds which involve the formation. The oil and gas present at the time the Etchegoin formation was overlapped moved toward the wedge edge. Later folding occurred which permitted higher reservoir space to be accessible to the oil and gas already accumulated along the wedge edge and further migration and localization occurred. The first and most important accumulation, therefore, of oil and gas in the Midway-Sunset district was that which occurred before the local folds were formed. Later folding merely readjusted the early accumulation to maintain conformity with the added structure.

The map and sections (Fig. 10) of the Appalachian oil and gas fields were compiled from various sources. Section *B* is an idealized section from west to east across the producing district in Pennsylvanian time. The Pennsylvanian formations are assumed to be deposited level and are used as the datum. At that time all of the older formations were dipping toward the east as evidenced by the thickening in that direction. Oil and gas in the reservoir rocks of pre-Pottsville age during Pottsville time would have moved up the dip toward the west until stopped by the wedging out of the reservoir rock. Later, as shown in *C*, the area was folded into many anticlines, some of which crossed the wedge edges of the reservoir rocks at varying angles. Higher ground was made accessible to the early edge accumulations and a redistribution of the oil and gas into higher folded areas occurred. Some anticlines were not in contact with the edge of the reser-

[10] R. W. Pack, "The Sunset-Midway Oil Field, California," *U. S. Geol. Survey Prof. Paper. 116* (1920).

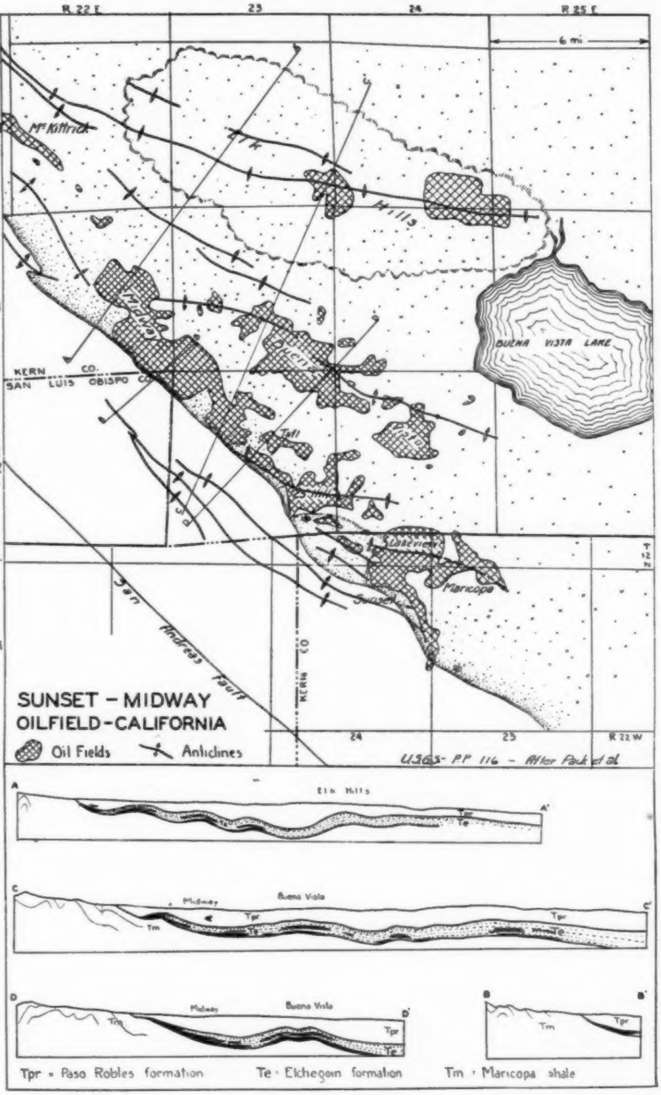

FIG. 9.—Map and sections of Sunset-Midway field, California. Adapted from report by Pack (*U. S. Geol. Survey Prof. Paper 116*). Oil pools cross-hatched and distribution of producing Etchegoin formation shown dotted.

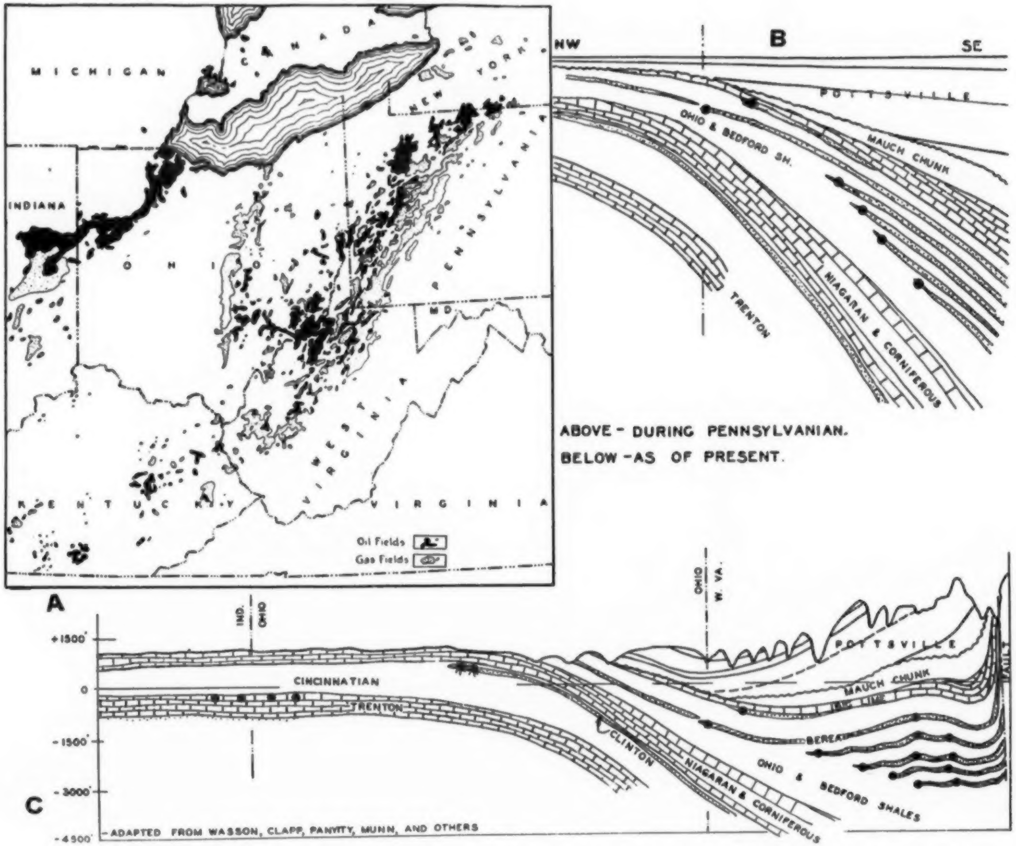

FIG. 10.—Map and geologic sections of Appalachian oil and gas fields. *A*, location of pools. *B*, idealized west–east section in Pennsylvanian time showing eastward dip of all older formations and oil and gas (black) accumulated at up-dip wedge edges of reservoir rocks. *C*, same section modified by later folding allowing redistribution of oil and gas into folds ac-

voir rock or were in such a position that no higher reservoir space was made available during the folding and they are now barren. The gas, being more volatile and mobile, moved farthest east away from the primary area of accumulation and the gas fields are now found generally along the east side of the district. Pools such as the Clinton sand gas pools in Ohio have been traps since the formation of the wedge edge of the Clinton sand and the readjustment to bring the gas and water into conformity with later folding has been relatively slight.

NORTHEAST TEXAS

Northeastern Texas, centering in the Tyler basin, is an excellent example of the application of paleogeology to the problem of the accumulation of oil and gas. The oil in this area is almost entirely obtained from the Woodbine sand of basal Upper Cretaceous age, and the chief producing areas and pools are the fault-line pools,[11] the East Texas pool,[12] the Boggy Creek pool,[13] and the Van pool. The geology of this area has been described by Powers[14] and by Wendlandt and Knebel.[15]

The Woodbine sand, which ranges from 500 to 800 feet in thickness in the Tyler basin and along the outcrop in the vicinity of Sherman and Denison, is wedged out along its south and east sides due to the convergence of unconformities below and above. The limits of the sandstone underground are shown dotted in Figure 11 and the outcrop is shown cross-hatched. The south and east sides of the Woodbine sand, therefore, were the high sides of the reservoir at the time the wedging-out process was completed and the edge overlapped by the Eagle Ford clay and the Austin chalk. The oil and gas in the Woodbine sand at that time migrated up the dip into the high sides of the reservoir and were trapped along the south and east wedge edges. The initial movement, therefore, must have been toward the

[11] Frederic H. Lahee, "Oil and Gas Fields of the Mexia and Tehuacana Fault Zones, Texas," *Structure of Typical American Oil Fields*, Vol. 1 (Amer. Assoc. Petrol. Geol., 1929), pp. 304–88.

[12] A. I. Levorsen, "The Geology of the East Texas Field," *Internat. Petrol. Tech.*, Vol. 8, No. 7 (1931), pp. 261–68.

[13] H. J. McLellan, E. A. Wendlandt, and E. A. Murchison, "Boggy Creek Dome, Anderson and Cherokee Counties, Texas." *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 6 (June, 1932), pp. 584–99.

[14] Sidney Powers, "Interior Salt Domes of Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 10, No. 1 (January, 1926), pp. 1–60.

[15] E. A. Wendlandt and G. M. Knebel, "Lower Claiborne of East Texas with Special Reference to Mount Sylvan Dome and Salt Movements," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 10 (October, 1929), pp. 1350–61.

east and south in so far as the present distribution of the Woodbine sandstone is concerned.

During Upper Cretaceous time the Sabine uplift of Louisiana and northeast Texas began to form, as shown by the thinning of the formations, and a low uplift crossed the eastern wedge margin of the Woodbine sand in southern Rusk County, thus allowing a further localization of the oil and gas already accumulated along the eastern wedge edge. During Tertiary time the Sabine area was folded again and the Tyler basin took form. A still further localization of oil and gas occurred, bringing them into adjustment with the changing structure. Faulting became prominent and the Mexia-Tehuacana fault zone de-

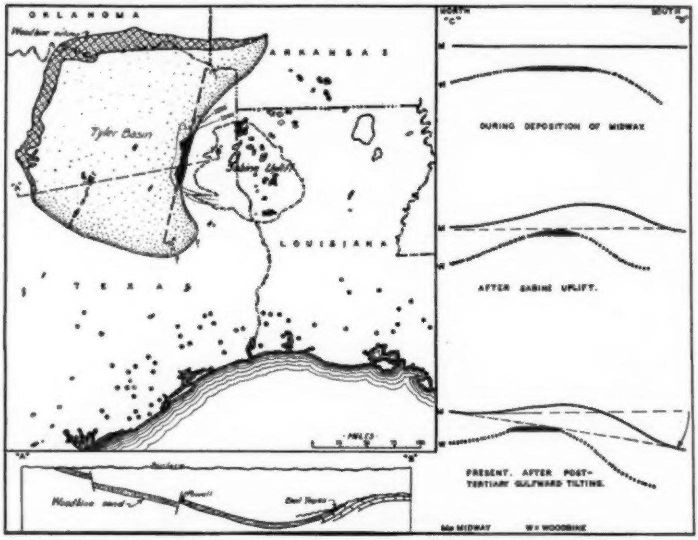

FIG. 11.—Extent (dotted) and outcrop (cross-hatched) of Woodbine sand in northeastern Texas. Idealized cross section from west to east through Mexia and East Texas fields. Diagrams on right illustrate changing oil-water level to maintain adjustment with shifting structure.

veloped along the south side. Oil and gas moving westward up the dip and along the wedge edge of the Woodbine sand were trapped behind these faults. Those faults away from the edge area did not receive any oil; consequently, they are now barren.

Later, the entire Gulf Coastal region was tilted down toward the Gulf of Mexico; and the Tyler basin, instead of being a deep closed

basin, was changed to a shallow basin nearly open toward the south. The evidence of the regional gulfward tilting in post-Tertiary time is found in the Midway formation, basal Tertiary in age, which because of its persistence and uniform thickness in wide areas must have been deposited nearly level, though it now has a dip gulfward where encountered. All post-Midway formations are involved and the gulfward tilting may be continuing at present. The eastern edge of the Woodbine sand extending for 50 miles north and south through Rusk County was therefore depressed at its south end 2,000–2,500 feet since Tertiary time. As the present water-oil contact in the East Texas field is in nearly perfect adjustment with the present structure, it may be assumed that the oil in the vicinity prior to the gulfward tilt has moved northward to maintain the gravity and sea-level adjustment. The movements are illustrated in the diagrams on the right side of Figure 11. The gas now found at the south end of the East Texas field may represent a remnant of the early accumulation.

ILLINOIS FIELDS

The pre-Pennsylvanian areal paleogeologic map shown in Figure 2 indicates the overlapped wedge edge of the Upper Mississippian as forming a U shape extending from Pennsylvania through Texas and Arizona to Montana. The one place along the 3,500 miles of wedge edge where the Upper Mississippian rocks have porosity sufficient to contain oil and gas, and also are buried under overlapping Pennsylvanian formations, is in Illinois. It is interesting to note that in eastern Illinois, where this wedge of alternating porous and non-porous Upper Mississippian rocks is unconformably overlapped by alternating sands and shales of the Pottsville group, and where this northward wedging group of Upper Mississippian and Lower Pennsylvanian formations is crossed by the south pitching La Salle anticline are now found the very productive oil fields of Crawford and Lawrence counties.

HUNTON AND CORNIFEROUS LIMESTONE POOLS

The pre-Mississippian paleogeologic map (Fig. 1) shows the wedge edge of the Devonian system surrounding the anticlinal axis extending from the region of Utah and Wyoming to Tennessee. Any oil or gas in the Devonian rocks at the time of its being overlapped by the Mississippian and through Mississippian time would tend to migrate up the dip toward the wedge edge. As later folding, faulting, and uplifting occurred, the oil and gas continued to seek the highest level within the reservoir rock. As the Devonian rocks are generally limestone in this area, the porosity is irregular and the final location of

the oil and gas was the result of complex local relations of the original wedge edge to variable porosity and permeability, to later folding and faulting, and to regional tilting. The Hunton limestone pools of Oklahoma and Kansas are closely related to the buried wedge edge of the Hunton limestone, as are the Corniferous limestone pools of Kentucky closely related to the buried wedge edge of the Corniferous limestone.

Conclusions

Paleogeology, and particularly the preparation and use of paleogeologic maps, offer a new approach to many geologic problems. A liberal use of isopachous maps in conjunction with the paleogeologic maps, throws light on many stratigraphic problems: source of sediments; shore lines and sea ways; overlaps; structure; unconformities; geologic history; and oil and gas accumulation.

Thousands of miles of wedged-out edges of possible reservoir rocks are shown on the three paleogeologic maps presented with this article. When it is remembered that these represent only three widely separated moments in geologic history and that countless additional maps remain to be compiled, some idea may be gained of the magnitude of the problem. The search for these buried wedge edges is certain to occupy the increasing attention of petroleum geologists as the supply of strictly anticlinal oil and gas prospects diminishes and the need for new petroleum resources increases. In the search for petroleum resources, an almost unlimited field of profitable geologic activity is revealed in the application of paleogeology to areas which have heretofore been considered barren.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 9 (SEPTEMBER, 1933), PP. 1133-1145

GEOLOGICAL NOTES

INFLUENCE OF SPEED OF MIGRATION OF OIL ON WATER ENCROACHMENT AT CASMALIA, CALIFORNIA[1]

The Casmalia oil field is in northern Santa Barbara County, California, 4 miles from the Pacific Ocean, and about 8 miles southwest of the town of Santa Maria.

The old Schumann wells west of the present field were probably drilled about 1900, though little is known of their histories excepting that in 1920, or near that time, commercial quantities of oil were shipped from the sump accumulation, and that at present two of the wells produce some gas. Probably the first well in the field proper was the old P.O.T. No. 1 which was completed in 1904 at a depth of 2,485 feet. It has been plugged back and is now known as Arellanes 91, a commercial producer at present.

Important development commenced in 1917 on such a scale that several hundred men were employed. During this period many wells had an initial production of 400–500 barrels per day with very little water.

Then suddenly in the spring of 1918 large amounts of water entered the field. Within a month one well increased its water content from 4 per cent to 45 per cent. A plugging program was tried but proved on the whole unsuccessful, and in 1925 the field was shut in. Marked suitability of the oil for the manufacture of asphalt and allied products, and favorable transportation facilities caused the field to be re-opened in the spring of 1931 by the Casmite Company. Since 1931 satisfactory commercial production has been maintained from the old wells.

Oil occurs in a well defined anticline having no structural complexities of importance. However, it is interesting that the anticlinal control theory holds only by coincidence. The gravity of the oil is about 8°–9° A.P.I. Being heavier than water, the oil should be in the syncline, not on the anticline. But the underground temperature hap-

[1] Read before the Pacific Section of the Association at the Los Angeles meeting, November 3, 1932. Manuscript received, April 21, 1933. Published with permission of the O. C. Field Gasoline Corporation and the Casmite Company.

pens to be high enough to raise the gravity of oil in the formation to 11°–12° A.P.I., which increase is sufficient to float the oil into the anticline.

Wells are commenced in the "blue shale," a gray slightly organic clay shale of probable Santa Margarita (upper Miocene) age. Below

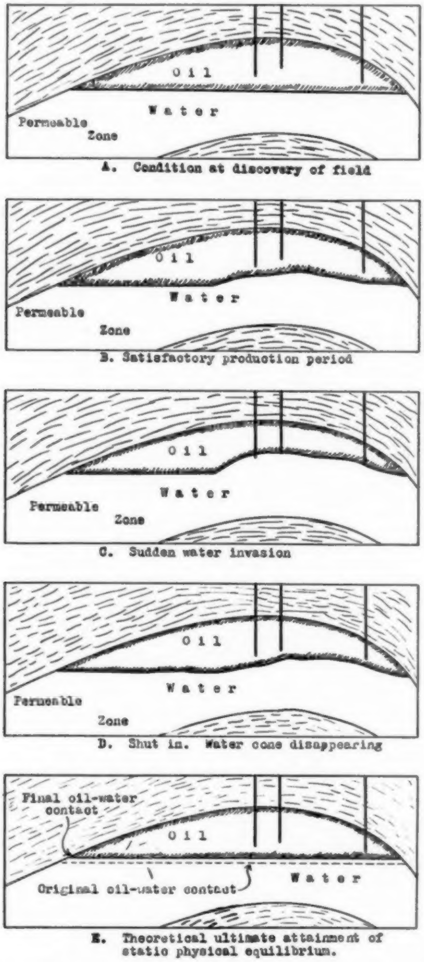

FIG. 1.—Hypothetical illustrations of formation and disappearance of water cone in oil field. Condition at Casmalia at present seems to be between D and E.

the "blue shale" which is approximately 800 feet thick, is the Monterey "brown shale" in which the productive zone lies. The oil evidently occurs in the joints and fractures of a particularly brittle zone in the Monterey at depths of 1,500–2,000 feet from the surface. Where sufficiently fractured the brittle shale is a granulated mass having the physical characteristics of sand, and it has often been mistakenly logged as sand.

A study of the sudden rapid invasion of water, and the partial rejuvenation after the 6-year shut-down indicates that: (1) the water is not definitely related to stratigraphic conditions, but may occur at one horizon in one well, and at a different one in another; (2) the invasion of water is irrespective of structure; that is, wells drilled on the same structure contour may encounter very different water conditions; (3) the invasion of water is definitely related to the property line along which competitive concentrated production took place.

The formation of a water cone, a process generally known and well illustrated by experiments described by H. D. Wilde, Jr., and F. H. Lahee,[2] seems the most plausible explanation of conditions at Casmalia.

When a volume of oil is removed at the pump its place is taken by more oil moving laterally and upward from the bottom toward the pump. In a condition such as that at Casmalia where there is no impervious layer immediately beneath the oil, the entire accumulation of oil is underlain with water. Hence the removal of a volume of oil at the pump results in a slight rise of water directly beneath the pump. If the system is highly fluid the upward projection of water into oil is almost immediately nullified, and the entire plane of the oil-water contact rises slightly. If oil is continuously removed, the oil-water surface rises in the manner conversely illustrated by the lowering of the surface of lemonade in a glass when liquid is removed through a straw.

If the system is not sufficiently fluid the viscosity lag prevents this rapid distribution of the rise over the entire water-oil contact surface. There is, instead, a local rise of water into oil, and due to viscosity this local rise maintains itself for a measurable and perhaps economically important period of time. Under such conditions, when oil is continuously removed, as in oil-field production, the system becomes *dynamic*. Water rises into oil in violation of equilibrium principles governing a static condition which, due to viscosity, require time for their operation. If the speed of production is too great to allow the

[2] "Simple Principles of Efficient Oil-Field Development," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 17, No. 8 (August, 1933), pp. 981–1002.

time required by the viscosity for ordinary static adjustment the slight cone of water into oil does not have time to flatten before more oil is removed. Therefore as oil is removed the water cone extends farther up into the oil until the tip of the cone reaches the well. The arrival of the tip of a water cone at the pump (or pumps) results in sudden highly increased water production such as that which occurred at Casmalia.

Once a water cone is in contact with a well the facility of water percolation as compared with viscous oil percolation permits an excessive proportion of water to be delivered to the pump.

A water cone is an equilibrium condition that can exist only in a dynamic environment such as that in an operating oil field. In a static environment the continued existence of a water cone of 10° gravity up into oil of 11° or 12° gravity is impossible. Hence, during the static period of shut-down from 1925 until 1931, ordinary physics would require that the water cone partly disappear, and apparently it has partly disappeared. The rate at which a cone might disappear is not known. It can be stated, however, that the 6-year shut-down period was sufficient for commercial rejuvenation of the field and satisfactory production with no important water increase from March, 1931, to date. D. M. Prentice, superintendent for the Casmite Company, has successfully adapted and developed the use of distillate in handling the low-gravity oil, and this method with a production program of rotation and resting the wells to allow the slow migration of the heavy oil through the formation has yielded satisfactory results.

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NEW MAJOR OIL FIELDS OF APSHERON PENINSULA, U.S.S.R.

For the last three years the Russian oil industry experienced a sharp contraction of crude oil production. The daily average output of all Russian fields was 428,336 barrels during 1931, declining to 409,070 barrels during 1932, and to 379,319 barrels during the first six months of 1933. Considering that all plans were made for continuously increasing supply of crude oil, the deficiency reached major proportions early in 1933.

The decline in crude oil production was due principally to the exhaustion of oil fields of Baku and Grozny, while the newly dis-

covered major fields of Sterlitamak, Neftedag, and Berekei lay either far away from transportation facilities, or were located in difficult mountainous country, delaying their development under Russian conditions for many years.

Therefore the discovery of additional major fields on the Apsheron Peninsula within a few miles from the existing trunk pipe lines, sea loading terminals, and large refineries is an event of major importance not only to the Russian oil industry, but also internationally, giving Russia a free exportable surplus of relatively cheap products.

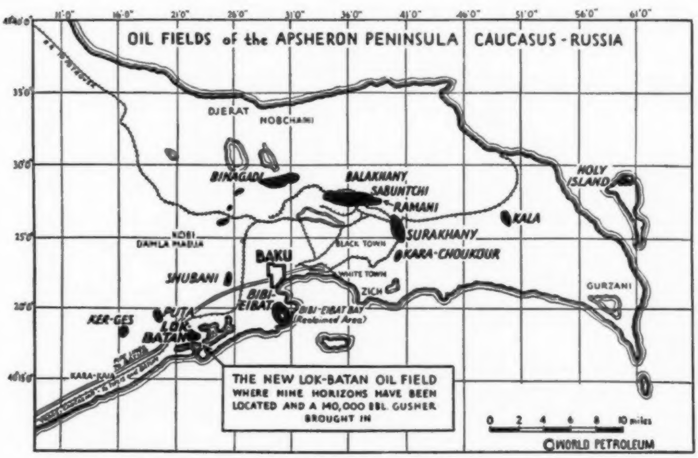

FIG. 1.—Map by courtesy of *World Petroleum* (August, 1933), p. 249.

The discovery of primary importance is the Lok Batan field located about 6 miles southwest from the Bibi-Eibat pool. The first well was commenced in Lok Batan in 1931 and was completed in May of 1932 with a production of 7,000 barrels per day. Currently there are in Lok Batan 10 producing wells and 6 drilling, 2 of the completions ranking among the largest gushers ever completed. Well No. 18 produced 70,000 barrels in the first 18 hours, and well No. 45 produced between 105,000 and 140,000 barrels per day from 1,725 feet for an extended period of time, installed pumps running to capacity and actually removing to storage 100,000 barrels daily, with large additional volume being collected in earthen reservoirs. Subsequently well No. 46 was completed, producing 42,000 barrels per day from 1,825 feet. As a result of these large wells, in May of 1933 Lok Batan field produced 975,000 or 10.7 per cent of total Baku district produc-

tion. The present proved area in Lok Batan is estimated at 850 acres, and it is believed probable that an additional 1,000 acres may produce. Considering that the Bibi-Eibat field averaged to date 516,000 barrels per acre, and is still producing, the Lok Batan field may represent a proved reserve of 440 million barrels and possibly of 950 million barrels if the larger acreage estimate is proved correct.

In the same general area of Lok Batan two smaller fields have been also developed within the last few years by the Soviet Government. In the Puta field there are now 45 producing wells and 11 drilling, with production opened to 2,400 feet, and wells ranging up to

FIG. 2.—Well No. 1, Lok-Batan field. Two mud-volcano cones seen in distance. Courtesy Amtorg Trading Corporation, New York.

5,000 barrels per day initially and about 2,000 barrels per day settled. In the Kergez field seven producing wells have been completed, averaging about 2,500 barrels per day initially, though well No. 96 produced 17,500 barrels per day. The Puta and Kergez fields are both small areally to date, the first estimated to cover 420 acres, and the second 250 acres. On the eastern end of the Apsheron Peninsula oil was finally discovered on the Kala structure after intermittent wildcatting since 1910. Three wells recently completed are averaging

17,500 barrels of light crude oil per day, with well No. 17 producing 7,000 barrels daily.

All new discoveries are producing from the "Oil measures" of Pliocene age. In the Lok Batan, Puta, and Kergez fields only the upper and central zones of the measures have been tested, and the lower zone is considered as proved, because it produces in the Bibi-Eibat field. A geologically very important fact in newly discovered fields of the Puta district is the further proof that the mud volcanoes affect only an extremely limited area and that wells drilled even on the side of mud volcanoes in the breccia find the regular geological column after passing through 100–150 feet of volcanic matter. Thus, in the Lok Batan field, well No. 45 was drilled on the side of the mud volcano, as were also wells No. 14 and No. 15, both large completions. Similarly in the old fields the Boga-Boga mud volcano is located in the middle of Balakany-Sabunchi-Ramani field, and two mud volcanoes are located on top of the Binagadi structure, and one has been found in the middle of the Bibi-Eibat field. Thus, with further developments, mud volcanoes, far from being objectionable features to staking wildcasts on pierced structures, as originally thought, appear to be definitely and favorably related to large oil accumulations. Considering that mud volcanoes cover most of the western Apsheron Peninsula and extend over a large area on the mainland into the Kabristan and Saliani steppes, and cover profusely as well the Taman and Kerch peninsulas of northwestern Caucasus and Crimea, the prospective area open for immediate wildcatting is of immense dimensions.

BASIL B. ZAVOICO

NEW YORK, N. Y.
August 7, 1933

SIXTEENTH INTERNATIONAL GEOLOGICAL CONGRESS

The sixteenth International Geological Congress convened in Washington on Saturday, July 22, and adjourned the following Saturday, July 29. This is the first time the Congress has met in the United States since 1891. The previous meeting was held in South Africa, in 1929, the one before that in Spain, in 1926, and the next meeting will probably be held in Russia, in 1936, as the Congress ordinarily meets once in three years.

The officers of the Congress were as follows: honorary presidents, Honorable Franklin D. Roosevelt, president of the United States, Honorable Herbert Hoover, ex-president of the United States;

honorary vice-presidents, the Secretary of State of the United States, the Secretary of the Interior of the United States, the director of the United States Geological Survey, the director of the United States Bureau of Mines, the president of the Geological Society of America, the president of the American Association for the Advancement of Science, the president of The American Association of Petroleum Geologists, the president of the American Institute of Mining and Metallurgical Engineers, and the president of the National Academy of Sciences; president, Waldemar Lindgren; general secretary, W. C. Mendenhall; general treasurer, Edward B. Mathews; assistant secretaries, H. G. Ferguson, M. I. Goldman; administrative assistant, Olive C. Postley; business manager, R. C. Becker.

The official delegates of the A.A.P.G. were: K. C. Heald, O. B. Hopkins, H. D. Miser, David White, F. W. DeWolf, L. C. Snider, Ralph D. Reed, Alexander Deussen, E. DeGolyer, and James H. Gardner. All but the last three were in attendance.

The week in Washington was spent in reading and discussing papers on all phases of geologic thought, by eminent authorities from many parts of the world. English was the official language of the Congress, but many papers were delivered in French, German, Spanish, and Italian.

Two sessions were held daily, from 10 A.M. to 12:30 P.M. and from 2:00 to 4:30 P.M., and on most days, two sections were in session at the same time. A total of 163 papers appeared in the program, of which about 50 were read by title; 25 of the 163 were by A.A.P.G. authors, both foreigners and Americans. Time allotted for each paper ranged from 10 to 20 minutes, and discussion from 5 to 10 minutes.

The general topics discussed were as follows: Measurement of Geologic Time (10 papers), Batholiths and Related Intrusives (19 papers), Zonal Relations of Metalliferous Deposits (8 papers), Major Divisions of the Paleozoic Era (17 papers), Geomorphogenic Processes in Arid Regions and their Resulting Forms and Products (13 papers), Fossil Man and Contemporary Faunas (9 papers), Orogenesis (28 papers), Geology of Petroleum (10 papers), Geology of Copper Deposits (4 papers), Miscellaneous Ore Deposits (5 papers), miscellaneous (20 papers).

It has been the custom of the International Geological Congress to select some particular mineral as a resource topic, and to publish a monograph covering the subject. "Petroleum Resources of the World" was originally chosen, but since this topic has been so fully covered in recent publications of the A.A.P.G. and elsewhere, it was thought that the Congress could be of greater service if another topic

was chosen, and it was decided to consider, instead, the "Copper Resources of the World."

Papers of interest to petroleum geologists were found in the sections on the Geology of Petroleum, the Major Divisions of the Paleozoic Era, Orogenesis, and the miscellaneous papers.

In the section on the Geology of Petroleum, J. A. Broggi, of Peru, pointed out the important role of tectonic forces in oil accumulation, and the value of tectonic-genetic maps as a key to areas most likely to be underlain by oil accumulations.

L. M. Goubkin, director of the United Geological and Prospecting Service of the U. S. S. R., discussed the tectonics of the southeastern Caucasus and its relation to productive oil fields, and pointed out the relation of diapirism in the accumulation of petroleum, the connection between the tectonics and the petroleum occurrences, and the connection between mud volcanoes and the oil fields of the Baku district.

A. I. Levorsen, of Tulsa, pointed out the importance of the wedge-edge of certain oil reservoirs in the occurrence of oil fields, and showed the value of paleogeologic maps (areal maps of various geological periods, as at the beginning of the Pennsylvanian) in locating the areas in which wedges occur.

Frank R. Clark, of Tulsa, discussed the origin and accumulation of oil, questioning the theory of long migration from widely disseminated sources, and suggesting rather local, rich accumulations of organic matter in close proximity to reservoirs.

Miss Taisia Stadnichenko, of the United States Geological Survey, reviewed some experiments in which boghead coals, cannel coals, oil shales, and carbonaceous shales were subjected to high pressures and temperatures and studied microscopically. The results suggest that the petroleum found in our oil fields may contain products generated at several stages in the long course of devolitilization of the organic matter in sediments.

Wallace E. Pratt, of Houston, in "Hydrogenation and the Origin of Oil" suggested that some light oils may have been formed by a process similar to the commercial process of hydrogenation, through the incorporation of methane directly into unsaturated heavy oils.

Five other papers on the geology of petroleum appeared on the program and were read by title: John M. Muir, "Limestone Reservoir Rocks in the Mexican Oil Fields, with a Discussion on the Origin of Oil"; Stanislav Zuber, "The Ponto-Caspian and Mediterranean Type of Oil Deposits"; Stanislav Zuber, "Paleogeography of the Oil-Bearing Deposits in the Ponto-Caspian Countries"; Parker Trask, "Some

Studies of Source Beds of Petroleum"; and Yoshinosuke Chitani, "The Petroleum Resources of Japan."

Under the general heading of the Major Divisions of the Paleozoic Era, divided into three sections, Lower, Middle, and Upper, several papers were presented by leading authorities of Europe, Asia, Africa, Australia, and North America, which resulted in exchanges of divergent ideas and lively discussion.

The papers included descriptions and distribution of the rocks of various formations in different countries, suggestions as to correlations with other parts of the world, and comments as to the proper place to draw systemic boundaries. The last resulted in interesting arguments among paleontologists, paleobotanists, and stratigraphers, and showed several schools of thought among the members of the Congress.

The Lower Paleozoic section discussed Britain, Spain, and Bohemia, the Cambro-Ordovician boundary in Asia, the Ordovician-Silurian boundary in Europe, the Devonian-Carboniferous boundary, and principles for the correlation and classification of strata.

The Middle Paleozoic section dealt with northwestern Europe, China, North America, Russia, and Japan; with floras and faunas; and Grabau astounded the meeting by advancing a new principle in stratigraphy—pulsation as against oscillation. He stated that stratigraphic investigations point to a rhythmic pulsation or rise and fall of the sea-level as of primary significance, with land movements effecting secondary modifications. Positive pulsation implies almost universal marine transgression and widespread deposition of representative formations. The succeeding negative pulsation implies almost universal retreat of the sea, with the formation of continental deposits, or with extensive erosion. This forms the basis of a threefold subdivision of the systems, in one of which the lower and upper divisions are transgressive, and the middle regressive, whereas in the succeeding system, the lower and upper divisions are regressive and the middle transgressive.

R. C. Moore suggested a new classification of the Middle Paleozoic, dividing the Pennsylvanian and Mississippian at the top of the Morrow and Bend because of widespread uplift and erosion at that time, and ending the Pennsylvanian with the base of the Triassic because of the lack of important unconformities below that point. He would abandon the terms "Carboniferous" and "Permian," and stated that this classification accords with conditions in all parts of the world.

The Upper Paleozoic section dealt with the Permian of Australia,

Gondwanaland, China, Russia, and North America, with general, widespread correlations, and showed some divergence of opinion.

W. J. Longmans of the Netherlands, in the Middle Paleozoic section, and Maxim K. Elias of the Kansas Geological Survey, in the miscellaneous section introduced some doubt as to the absolute value of fossil plants in broad correlations. Longmans contended that the presence of the same species in widely distant regions is no proof of strictly contemporaneous deposition. Certain living floral assemblages are of a type which elsewhere prevailed in the Tertiary, and similar conditions may have occurred in the Paleozoic.

Elias announced the finding of numerous remains of *Walchia piniformis* and other "Permian" plants in the Lawrence shale at Garnett, Kansas, below the rich Stephanian (upper Pennsylvanian) flora of the Lawrence shale (White and Sellards). This is the lowest known stratigraphic occurrence of the *Walchia* flora in America. He concluded that the Pennsylvanian-Permian boundary may not necessarily conform to the local vertical distribution of the plant assemblages which indicate repeated changes in local environment through geologic time.

A. A. P. G. members whose papers appeared on the program included: Hans Stille, R. J. Holden, Alfred C. Lane, Stanislav Zuber, I. M. Goubkin, A. I. Levorsen, Frank R. Clark, Wallace E. Pratt, John M. Muir, Parker D. Trask, Edwin T. Hodge, Teiichi Kobayashi, Raymond C. Moore, David White, Charles Schuchert, Donald C. Barton, Eliot Blackwelder, W. H. Emmons, W. S. Behre, Robert H. Dott, and Hugh D. Miser. Approximately 175 A. A. P. G. members registered for the Congress, and a rough check of those present indicates that approximately 75 or 100 attended the sessions.

All technical and business sessions were held in the building of the United States Chamber of Commerce, and for two days the Congress had to compete in interest with the hearings on the oil industry code, which were held in the same building. The night meetings, which included popular talks and comprised the principal entertainment for the sessions, were held in the ball room of the Shoreham Hotel.

The entertainment consisted of a tea on Sunday afternoon, given at the home of Dr. and Mrs. Whitman Cross, in Chevy Chase. Saturday night a smoker was given by the Geological Society of Washington, at the Shoreham, preceded by an address by Douglas Johnson on "A Geomorphic Traverse of the United States." On Sunday night Hellmut de Terra gave an interesting address on a journey of scientific explorations to the Himalayas and Eastern Karakoram, illustrated with lantern slides and motion pictures.

On Monday night the motion picture "The Evolution of the Oil

Industry," prepared by the United States Bureau of Mines, was shown. On Tuesday night, Frank Dawson Adams, professor emeritus of McGill University, delivered an address on Lyell, in commemoration of the 100th anniversary of the completion of Lyell's *Principles of Geology*. An address on Albert National Park, Belgian Congo, was scheduled for Wednesday night, but was cancelled. At one of the technical sessions Tuesday, it was announced that a round table discussion for those interested in the problem of the Ozarkian, would be led by E. O. Ulrich, and it was expected "that a good time would be had by all." On Thursday night a reception was tendered the members of the Congress by the National Academy of Science, in its beautiful building at 21st Street and Constitution Avenue. Tea was served each afternoon at 4:30 in the Chamber of Commerce Building.

Throughout the week, special entertainment, mainly in the form of sightseeing, was provided for the women visitors, and many of the national shrines in the vicinity of Washington were visited, including the Arlington Cemetery and the Lee Mansion, the Lincoln Memorial, the Washington Monument, and Mount Vernon.

Preceding, during, and following the Washington meeting, excursions were taken by members of the Congress to many parts of the United States. In the two weeks preceding, trips were taken through New England and eastern New York, through the mining districts of the southeastern and central states, through the Appalachian valley in Virginia and neighboring states, to study the Paleozoic stratigraphy of New York, over the coastal plain of the Chesapeake Bay region, through the oil fields of Oklahoma and Texas, to study the geomorphology of the central Appalachians, through the mineral regions of New Jersey and eastern Pennsylvania, and across the continent from San Francisco to Washington, for the benefit of those coming from the Pacific Coast.

During the sessions, short trips were taken in the general vicinity of Washington, including one to Harrisburg, Pennsylvania, to study Appalachian structure, one to the Cornwall iron mines near Harrisburg, one to study the pre-Cambrian geology of northern Maryland and southern Pennsylvania, one to study the geomorphology of northern Virginia, one to study the Appalachian stratigraphy and structure in Virginia, one to the titanium and soapstone deposits of Virginia, one along the coastal plain of southern Maryland, and another to the scientific institutions of Washington.

Following the sessions, excursions were taken across the continent by way of New Mexico and Arizona, returning through Utah, Colorado, and the Century of Progress Exposition at Chicago. Another

passed through Kansas City, across Kansas, to the Grand Canyon, and to Los Angeles, and returned by way of Crater Lake, Yellowstone, the Black Hills, and Chicago. A third studied the glacial deposits in Illinois, Iowa and Wisconsin. A fourth went to the iron and copper areas in the Lake Superior region.

All members attending the sessions were supplied with a program, a small book containing a preliminary list of registrants, another containing abstracts of papers, a small leather note book bearing the member's name in gold leaf, copies of 30 guide books covering all excursions, and a copy of the new United States Geological Survey map of the United States on a scale of 1:2,500,000. The guide books and map will be sent to all registrants who did not attend the sessions. At some future date, when funds are available for publication, all members of the Congress will be furnished a copy of the *Proceedings*.

ROBERT H. DOTT

TULSA, OKLAHOMA
August, 1933

CRETACEOUS SEDIMENTS IN CROWLEYS RIDGE, SOUTHEASTERN MISSOURI

CORRECTION

In the geological note, "Cretaceous Sediments in Crowleys Ridge, Southeastern Missouri," in the *Bulletin*, Vol. 17, No. 8 (August, 1933), p. 1009, in the last list of fossils, the seven species *Crassatellities* to *Corbula* inclusive, erroneously listed under *Gastropoda* should be listed under *Pelecypoda*.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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RESEARCH NOTES

A. A. P. G. RESEARCH COMMITTEE

(Members' terms expire immediately after annual Association meetings of the years shown.)

DONALD C. BARTON (1936), *chairman*, Petroleum Building, Houston, Texas
M. G. CHENEY (1934), *vice-chairman*, Coleman, Texas

1934:
K. C. HEALD, Gulf Bldg., Pittsburgh, Pa.
F. H. LAHEE, Box 2880, Dallas, Tex.
H. A. LEY, Rio Oil Corp., Fort Worth, Tex.
R. C. MOORE, Univ. of Kansas, Lawrence, Kan.
F. B. PLUMMER, Bur. Econ. Geol., Austin, Tex.

1935:
C. E. DOBBIN, 523 Custom House, Denver, Colo.
A. I. LEVORSEN, 1740 S. St. Louis, Tulsa, Okla.
ALEX. W. MCCOY, 919 E. Grand, Ponca City, Okla.
C. V. MILLIKAN, Drawer 2040, Tulsa, Okla.
L. C. SNIDER, 60 Wall St., New York, N. Y.
L. C. UREN, Univ. California, Berkeley, Calif.

1936:
HAROLD W. HOOTS, Union Oil Co., Los Angeles, Calif.
R. S. KNAPPEN, Box 661, Tulsa, Okla.
W. C. SPOONER, Box 1195, Shreveport, La.
PARKER D. TRASK, U. S. G. S., Washington, D. C.

The purpose of the research committee is the advancement of research within the field of petroleum geology. If members working actively in research on particular problems care to register with the research committee, the committee will be glad to aid them in any way it can and put them in touch with other men who are, or have been, working on similar or allied problems and can perhaps effect some integration of the research work of the Association. If the younger, or older, members of the Association, who are doing or preparing research for publication, will come to any member of the committee, he will be very glad to offer whatever advice, counsel, or criticism he can in regard to the research, its prosecution, or its preparation for formal presentation. The committee would be glad to have members formulate and present to it suggestions in regard to research problems and programs.

LOCAL RESEARCH GROUPS

The research committee of The American Association of Petroleum Geologists is interested in stimulating the formation of local research groups. The purpose which the committee has in mind is: first, to stimulate the spirit of research, both in the older and the younger men; second, to further coöperative research by different individuals and different groups, and fundamentally to promote research on the basically important problems of petroleum geology. Many company geologists do much research as part of their work. But a very great many of the younger company men and many of the older company men do not have access to research problems and data.

or at least, to problems and data which can be used in publication of results of research. Some of the more fundamental problems of oil geology perhaps can be attacked best by coöperative research by several or many men or by many groups. If in any local oil area, men interested in doing research outside of the line of their company duty will get together and form a local research group and will consult with the research committee and with the senior research men of the distiict, practicable research problems probably can be found for men who do not have them, and raw data can perhaps be made available which would not otherwise be available.

Each local research group presumably would govern its own conduct and membership and would organize like a seminar class and meet weekly, biweekly, or monthly to discuss progress in the research. The local group could organize its own research and the coöperation between its members. The research committee would stand ready to aid the local group with advice, support, and criticism, and to arrange coöperation between local groups; and would attempt to promote coöperative research by several or many groups on a few of the more important fundamental problems of oil geology.

Any one who would be interested in joining such a research group should register with the nearest member of the research committee.

DONALD C. BARTON, *chairman*

FALL MEETING

In accordance with the request of chairman Barton, informal programs are being prepared for meetings of the members of the research committee and others who may be interested in topics discussed, for the current year. Following last year's precedent a fall meeting of the committee will be held on the mezzanine floor of the Baker Hotel, Dallas, Texas, at 2:00 P.M., Wednesday, October 5, the day preceding the meeting of the Petroleum Division of the American Institute of Mining and Metallurgical Engineers. The afternoon meeting will be followed by an evening meeting if found desirable. The main topic will be "Reservoir Rocks" and, more particularly, "The Preservation of Porosity in Sand Reservoirs" and "The Development of Porosity in Limestone Reservoirs." There will be speakers from different areas. F. B. Plummer, of Austin, will present a classification of reservoirs. Talks are expected by R. B. Whitehead and F. E. Heath of Dallas, E. Russell Lloyd of Midland, H. D. McCallum of San Antonio, Marcus A. Hanna of Houston, and others. Those who wish to contribute brief talks on papers on pertinent subjects are invited to do so and asked to advise the undersigned, as program chairman, in advance of the meeting.

It is hoped that these informal meetings will stimulate research among our members and lead to informative contributions for our *Bulletin*.

M. G. CHENEY, *vice-chairman*

COLEMAN, TEXAS
August, 1933

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 9 (SEPTEMBER, 1933), PP. 1148-1153

REVIEWS AND NEW PUBLICATIONS

Textbook of Geology, Part II, Historical Geology. By CHARLES SCHUCHERT and CARL O. DUNBAR. Third edition, largely rewritten. (John Wiley and Sons, New York, 1933.) 551 pp. Price, $4.00.

This third edition of *Historical Geology* has been revised and largely rewritten from a somewhat less technical point of view than previous editions. Its aim is to tell a connected story of earth history with emphasis on the principles used in deciphering the historical record and with a conscious attempt to avoid irrelevant detail.

After introductory chapters on fossils and their meaning, evolution, origin of the earth, and geologic time, the geologic periods are treated in order according to a standard plan which includes a brief historical sketch of the origin of the period name; the physical setting and physical history of the period; correlation tables of formations in typical regions; climate of the period; and, finally, the life of the period, together with a discussion of evolutionary changes as compared with preceding periods. Brief historical and biographical sketches of the work of geological pioneers, introduced at the beginning of several of the chapters, add much to the interest of the story. The treatment of the paleogeography and physical history of each of the periods provides an effective setting for the discussion of the rock formations deposited during that period and for its evolutionary changes because it relates them as cause and effect.

At the end of the book is a 42-page appendix—"An Introduction to Animals and Plants"—which the reader not well versed in zoölogy would profit by reading in advance of the body of the book. It is well illustrated by examples of the various plant and animal phyla and includes clear and interesting descriptions of special structures and organs and their uses.

The book is primarily an introductory text, not an exhaustive reference work. It is very well written and well illustrated. It tells a connected story in such a way that the fact that it is a text is likely to be forgotten.

JOHN L. RICH

OTTAWA, KANSAS
August 3, 1933

"The Geology of the Blue Springs Gas Field, Jackson County, Missouri." By GLENN G. BARTLE. *Missouri Bur. Geol. and Mines 57th Bienn. Rept. State Geologist* (Rolla, 1933), Appendix III. 64 pp., 1 fig., 5 pls.

The biennial report of state geologist H. A. Buehler for the period 1931–32 includes a number of most excellent and timely contributions to the geology and mineral resources of Missouri. In general, the high character of the publication indicates that the Missouri Bureau of Geology and Mines continues to maintain its rank as one of the best in the United States. If all other expenditures of public funds were as wisely managed as those handled by Dr. Buehler, the problem of taxation would certainly become less acute.

However, the report includes a paper by Glenn G. Bartle, entitled "The Geology of the Blue Springs Gas Field," which discusses the geology and gas reserves of a small area in Jackson County, an article which is below the usual high standard of Missouri geological publications. In dealing with the geology Mr. Bartle seems to have attached undue importance to the minor folds on the major anticlines, and overlooked the broader structural aspects of the field. His statement that "the synclines are the dominant structural features" (page 34), does not correspond with the facts as portrayed on the structural map.

The author devotes considerable space to criticism of the various methods of estimating gas reserves, and in particular assails the use of declines in rock pressure for the calculation of gas reserves. His general position is best indicated by the following quotations from his conclusions (page 54).

> The rock pressure decline curve method is not reliable. The decline of open flow method should be substituted for the rock pressure method and it must be based upon many wells and a reasonably long history of production.
>
> It is obvious that no empirical formula can be developed for the estimation of gas reserves. Each field must be studied with relation to its peculiar geological conditions and with respect to similar conditions in other districts.

From the graphs it appears that Bartle's conception of the use of rock pressure is as a function of time, while sound engineering requires the use of both rock-pressure decline and the production of the field during the period of the decline, without reference to the time factor. Where the author attempted to use these quantities, he failed to distinguish between the mathematical average of well pressures and the true average pressure of the gas field. Obviously he is unacquainted with methods for calculating weighted averages, or in the case of gas fields, with the necessity of taking into consideration the areal distribution of the various pressures.

Natural gas engineers and operators know that declines in pressure take place most rapidly in the areas from which largest quantities of gas are extracted, while the pressures in other portions of the field show little or no decrease. A definite pressure gradient is established from the undeveloped parts of the field toward those where withdrawals are concentrated. In order to apply this principle to the computation of field pressures, suppose that the area from which the greatest withdrawals have been made constitutes only 20 per cent of the entire field, then only 20 per cent as much weight should be given to the low-pressure area as to the undrained or high-pressure area in determining the average pressure of the field.

Bartle does not give complete well data, or state specifically how he obtained average pressures for the field, but it is clear that they were computed by dividing the sum of the pressures of all, or a portion, of the wells by the total number of wells used. Such a method of computing average pressures can not give accurate results unless withdrawals are uniform from all parts of the field, or the size of the field is so small and the permeability so great that the reservoir pressures are immediately equalized no matter how irregularly the wells are spaced or withdrawals made. On the other hand, if a weighted average pressure is calculated, the seasonal fluctuations in the rate of withdrawal, the variations in the number of wells operated, and the spacing program will have no effect on the result.

In such a small field, with relatively small pressure declines during the

various periods, slight errors in the average pressures have a very large effect on the calculated yield per pound drop in pressure.

For example, during the period from October 1, 1929, to January 1, 1930, Bartle reported a decline of 6.2 pounds, which gives a yield per pound drop in pressure of 48,927,000 cubic feet. If the actual drop in pressure had been 8.2 pounds, the yield per pound drop would have been practically 37 million cubic feet; an error of one pound each way in determining the average pressure would account for his erratic results. During the period from July 1, 1930, to October 1, 1930, a drop in the average pressure of 3.1 pounds is reported; if the drop in pressure had feen 6 pounds, the yield per pound drop would have been 37 million cubic feet. Similarly, for the period January 1, 1931, to April 1, 1931, his reported drop of 2.9 pounds, if corrected to 4.1 pounds, would again give the 37 million cubic feet per pound drop in pressure. Inspection of the accompanying chart, where rock pressure is plotted

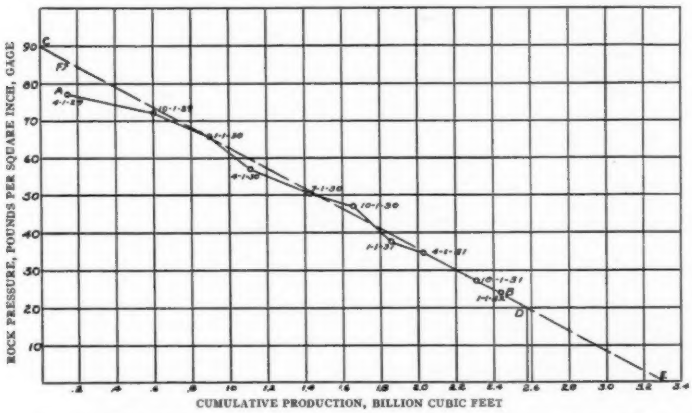

FIG. 1.—Blue Springs gas field, western district. Rock pressure-cumulative production chart.

AB: Data calculated from Bartle's figures.

CD: Average rock pressure-production data to 20-pound economic limit. Ultimate production at $D=2.58$ billion cubic feet. Ultimate production to atmospheric pressure or point $E=3.3$ billion cubic feet.

F: Corrected average rock pressure as of April 1, 1929 = 86 pounds.

against cumulative production, shows that the average pressures for both April 1, 1929, and October 1, 1929, were too low, while those of January 1, 1930, were too high. Further, Bartle's average pressure for October 1, 1930, is shown from the graph to be too high, while the drop in the average pressure for the period October 1, 1930, to January, 1931, is too great.

The writer's own data for the western district, as given on pages 36–37 and 47–53 have been recomputed as shown in the accompanying table, so that the total decline in pressure as of each date is divided into the total past production as of the same date (column *C* divided by *B*). Beginning with October 1, 1930, the yields per pound drop in pressures are well within the limits of engineering error in spite of the author's incorrect average pressures. The

TABLE I

SUMMARY OF DATA FOR WESTERN DISTRICT, BLUE SPRINGS GAS FIELD, JACKSON COUNTY, MISSOURI

	A	B	C	D	E	F	G	H
Date, Month-Day-Year	*Bartle's Drop in Average Pressure Since Preceding Date*	*Cumulative Pressure Drop, Pounds*	*Past Production, Million Cu. Ft.*	*Bartle's Corrected Yield per Cu. Ft. Decline in Open Flow*	*Ultimate Field Production (Open Flow of October, 1929, Times D)*	*Yield Per Pound Drop (Author's Method) Thousand Cu. Ft.*	*Yield Per Pound Drop (Cumulative Method) Thousand Cu. Ft.**	*Ultimate Production*** *Thousand Cu. Ft.*
4-1-29	...	12.9	149.4	.....	....	......	11,580	....
10-1-29	5.3	18.2	601.3	.....	....	85,262	33,038	2,312.6
1-1-30	6.2	24.4	904.6	62.4	2,985.7	48,927	37,073	2,595.1
4-1-30	8.6	33	1,167.9	24.0	1,148.3	30,614	35,390	2,477.3
7-1-30	6.7	39.7	1,427.9	.....	....	38,811	35,967	2,517.7
10-1-30	3.1	42.8	1,656.1	48.4	2,315.8	76,819	38,693	2,708.5
1-1-31	9.6	52.4	1,862.6	.....	....	21,473	35,545	2,488.1
4-1-31	2.9	55.3	2,031.8	37.5	1,794.3	58,332	36,741	2,571.8
10-1-31	7.7	63	2,314.7	121.7	5,823.1	36,740	36,741	2,571.8
1-1-32	3.	66	2,439.2	.....	....	41,503	36,957	2,586.9

* Column *C* divided by column *B*.

** Based on the product of column *G* times the drop in pressure from 90 pounds initial pressure to an economic limit of 20 pounds (gage pressures).

yield per pound drop in pressure, based on cumulative pressure drop and cumulative production, ranges, after April 1, 1929, from 33,038,000 to 38,693,000 cubic feet (column *H*), and the ultimate production to a 20-pound economic limit ranges from 2,312.6 million to 2,708.5 million cubic feet. If the average pressure readings for April 1, 1929, be corrected, as already noted, to 86 pounds, the yield per pound drop for the period involved becomes 37,347,000 cubic feet.

The accompanying table also shows the data used by Bartle for the western district (recomputed to eliminate arithmetical errors), and gives a comparison between the results based on decline in open flow and those based on yield per pound drop in pressure. (Unfortunately it is necessary to use Bartle's erroneous figures for average field pressures.) In column *D* the yield per cubic foot decline in open flow ranges from 24 to 121.7 cubic feet (pages 52–53), and the ultimate production obtained by multiplying this quantity (*D*) by the open flow as of October 1, 1929, ranges from 1,148.3 million to 5,823.1 million cubic feet. It is difficult to understand how Bartle failed to see that the total open flow is largely dependent on the number of wells, and that early in the life of the field the open flow continues to increase for a comparatively long time while the rock pressure is actually declining. No data are presented to show that such an increase in open flow did not take place, at least up to October 1, 1929.

Bartle may also be criticized for his failure to make use of original sources of material, and his neglect to cite adequately the literature dealing with

methods of estimating gas reserves and of testing the open-flow capacity. For example the following publications are not mentioned.

"Estimation of Gas Reserves," by Ralph E. Davis. *Oil and Gas Jour.* (June 18, 1927), p. 125

"Problems in Estimating Gas Reserves," by R. R. Brandenthaler. *Oil and Gas Jour.* (June 30, 1927), p. 40

"Accurate Estimates of Gas Reserves," by C. P. Parsons. *Oil and Gas Jour.* (May 10, 1928), pp. 86, 156, 189

"The Study of a Fundamental Basis for Controlling and Gaging Natural Gas Wells," by H. R. Pierce and E. L. Rawlins. *U. S. Bur. Mines Repts. Investigations 2929, 2930* (May, 1929)

"Standardizing the Open Flow from Natural Gas Wells," by R. R. Brandenthaler, E. L. Rawlins, and T. W. Johnson. *U. S. Bur. Mines Rept. Investigations 2885* (August, 1928)

Even the literature which Bartle has examined appears to have been misquoted or misunderstood, or both. His discussion (pages 44–45) of the work of Versluys indicates that the original article has not been comprehended. Versluys skilfully analyzes the pressure distribution in the wells, or the area, around a "venting" or discharge well during a period when both the production and pressures are measured, and these data form the bases for his equations. It is noteworthy that his equation number 23 approaches closely that derived experimentally by Pierce and Rawlins for the basic open flow of a well. Again (page 46), misquoting from Johnson and Morgan relative to the equal-pound-loss method of estimating gas reserves, Bartle makes the astonishing statement that "Methane, being a mixture of gases, does not follow Boyle's law." Not only are these authors misquoted, but Bartle failed to discover that the fallacy in their criticisms and in those of Brown was due to their common failure to recognize that the mathematical average of the well pressures is rarely the average pressure of the reservoir. Bartle's faulty logic is indicated by his proposal to use the decline in open flow as a measure of reserves while he also states (page 51), "the open flow of a gas well is a theoretical figure"! Not content with this surprising statement, Bartle then explains in the subsequent paragraphs how to measure this theoretical figure experimentally by means of a Pitot tube.

The only valid objection offered against the use of the rock-pressure production-decline method of estimating reserves is that the reduction in the volume of the reservoir which accompanies water encroachment tends to maintain the pressure. Engineers engaged in making such estimates have long been acquainted with this fact and use other methods under such circumstances.

Sound theoretical reasons are known for some analogy between decline in rock pressure and decline in open-flow capacity, but the total open flow of a field is definitely a function of the number of wells in operation, while the rock pressure at any time is an expression of a relatively simple relation between the original pressure and the quantity of gas which has been removed from the reservoir.

EUGENE A. STEPHENSON

ROLLA, MISSOURI
July, 1933

RECENT PUBLICATIONS

ARKANSAS

"Discovery of Rock Salt Deposit in Deep Well in Union County, Arkansas," by H. W. Bell. *Arkansas Geol. Survey Inform. Cir. 5* (Little Rock, 1933). 21 pp., mimeog.; 2 figs. 8¼×10¾ inches.

CALIFORNIA

Oil and Gas Fields of California. U. S. Geol. Survey (1933). Map of part of state, showing oil and gas fields. Scale, 1 inch = about 8 miles. Size, 64 by 44 inches. Supt. Documents, Government Printing Office, Washington, D. C. Price, $0.50.

GENERAL

"Les théories de MacKenzie Taylor sur les éxchanges de bases dans les argiles et la géologie du pétrole" (The Theories of MacKenzie Taylor on the Exchange of Bases in Shales and the Geology of Petroleum), by Jean Jung. *Annal. de l'Office Nat. des Combus. Liq.* (Paris, March-April, 1933), pp. 291–300.

"Miocene Foraminifera of the Coastal Plain of the Eastern United States," by J. A. Cushman and E. D. Cahill. *U. S. Geol. Survey Prof. Paper 175–A* (1933). 50 pp., 13 pls. Supt. Documents, Government Printing Office, Washington, D. C. Price, $0.15.

Geologic Map of the United States. U. S. Geol. Survey (1933). Scale, 1 inch = about 40 miles. 4 sheets, each 27 by 47 inches (when trimmed and pasted to make a single sheet, 51 by 90 inches). Supt. Documents, Government Printing Office, Washington, D. C. Price, $2.50.

GEOPHYSICS

Angewandte Geophysik fur Bergleute und Geologen (Applied Geophysics for Engineers and Geologists), by Hermann Reich. Part 1: 151 pp., 74 figs. Akademische Verlagsgesellschaft m. b. H., Leipzig (1933). 6¼×9¼ inches. Paper. Price, M. 12.60.

GERMANY

"Anwendung einer neuen sedimentpetrographischen Methode auf die Miozänstratigraphie und Tektonik im Erdgasgebiet von Neuengamme" (Use of a New Sedimentary Petrographic Method in Miocene Stratigraphy and Tectonics in the Gas Region of Neuengamme), by Wilhelm Georg Simon. *Kali, Verwandte Salze und Erdöl* (Halle, Saale, Germany, July 15, 1933), pp. 173–76, Figs. 4–7 (concluded from previous issue).

NEW MEXICO

Geologic Structure of the Southern Part of the San Juan Basin, New Mexico, compiled by C. B. Hunt and C. H. Dane. Advance structure map compiled from geologic maps to be published with full reports later. U. S. Geological Survey, Washington, D. C. (1933); R. R. Woolley, 313 Federal Building, Salt Lake City, Utah; Robert Follansbee, 403 Post Office Building, Denver, Colorado. Free.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 9 (SEPTEMBER, 1933), PP. 1154-1155

THE ASSOCIATION ROUND TABLE

SUPPLEMENTARY MEMBERSHIP LIST, SEPTEMBER 1, 1933

Members	17
‖Associates	14
Total additions since publication of list in March *Bulletin*	31

‖Broughton, M. N., Box 317, Camden, Ark.
Caster, E. L., Arkansas Nat. Gas Corp., Shreveport, La.
Clark, George H., Box 336, Livingston, Tex.
‖Davidson, John P., 814 City Natl. Bldg., Wichita Falls, Tex.
Dickinson, George, 18 Frederick Road, Wylde Green, Birmingham, England
‖Earl, Eugene L., 307 N. Monroe St., Waxahachie, Tex.
Etherington, Thomas, Richmond Petroleum Co., Barranquilla, Colombia, S. A.
Evans, Noel, 701 Continental Bldg., Oklahoma City, Okla.
Fralich, Charles E., Hooker-Fulton Bldg., Bradford, Pa.
‖Galley, John E., Shell Petroleum Corp., Box 1191, Tulsa, Okla.
Ginter, Roy L., 118 W. Cameron St., Tulsa, Okla.
‖Hemsell, Clenon C., Southern Carbon Co., Box 1346, Monroe, La.
‖Howard, Edward L., Box 334, Tyler, Tex.
‖Jones, Wayne V., 611 Giddens Lane Bldg., Shreveport, La.
Kalb, J. L., Lago Petr. Corp., Apartado 172, Maracaibo, Venezuela, S. A.
‖Lay, Roy L., The Texas Co., Box 2332, Houston, Tex.
Lilienborg, B. A., 1012 N. Rockford, Tulsa, Okla.
McCloskey, Downs, 300 D St., Bakersfield, Calif.
‖McCourt, James H., Montana Power Gas Co., Cut Bank, Mont.
‖McCutchin, John A., Box 37, Earlsboro, Okla.
McFarland, L. R., Box 4577, Capitol Hill Station, Oklahoma City, Okla.
Meents, Richard O., 514 E. Main St., Ada, Okla.
Olcott, David Perry, Box 887, Lake Charles, La.
‖Orr, Everett, Marlow, Okla.
Posey, Ellen, The Empire Cos., Bartlesville, Okla.
‖Ransone, William Robert, 1311 Republic Bank Bldg., Dallas, Tex.
‖Rupnik, John J., Geophysical Division, The Texas Co., Houston, Tex.
‖Sprague, Robert D., Box 1990, Fort Worth, Tex.
Townley, Enid, 905 S. First St., Champaign, Ill.
Wilde, Henry Dayton, Humble Oil & Refg. Co., Houston, Tex.
Wood, Douglas, British Controlled Oilfields, Ltd., Apartado 232, Maracaibo, Venezuela, S. A.

ASSOCIATION COMMITTEES

EXECUTIVE COMMITTEE

Frank R. Clark, *chairman*, Mid-Kansas Oil and Gas Company, Tulsa, Oklahoma
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Frederic H. Lahee, Sun Oil Company, Dallas, Texas
George Sawtelle, Kirby Petroleum Company, Houston, Texas
L. C. Snider, H. L. Doherty and Company, New York, N. Y.

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Parker D. Trask (1936)

REPRESENTATIVE ON DIVISION OF GEOLOGY AND GEOGRAPHY NATIONAL RESEARCH COUNCIL

R. S. Knappen (1934)

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Ira H. Cram
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TRUSTEES OF RESEARCH FUND

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Ford Bradish
Arthur E. Brainerd
H. A. Buehler
Hal P. Bybee
W. F. Chisholm
Herschel H. Cooper
Carey Croneis
Marvin Lee
S. E. Slipper
E. K. Soper
Luther H. White
R. B. Whitehead

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 9 (SEPTEMBER, 1933), P. 1156

Memorial

ALLAN EUGENE REIFF

Allan Eugene Reiff was born in Omaha, Nebraska, January 19, 1908. He died July 2, 1933, as the result of injuries he received two days earlier when run over on the street by an automobile in Omaha. He is survived by his parents, Mr. and Mrs. George H. Reiff, 1129 South 35th Avenue, Omaha, Nebraska, a brother, Stanley G. Reiff, and two sisters, Mrs. Doris Field and Mrs. Phyllis Fleming, of Omaha, Nebraska.

Allan attended grade schools in Omaha and graduated from Omaha Central High School in June, 1925. In the fall of the same year he entered the University of Nebraska and graduated in May, 1929, receiving a Bachelor of Science degree with a major in geology. In June, 1929, he entered the employ of Producers and Refiners Corporation, geological department, with headquarters in Tulsa, Oklahoma. On May 1, 1930, he was transferred to the San Antonio office of the same company and served there in the capacity of geologist until May 15, 1931, when the company closed their San Antonio office. After a short course in the government flying school at Randolph field in San Antonio, Allan returned to Omaha and entered business as a partner in the Truck Terminal and Supply Company of that city.

Allan was a member of Phi Gamma Delta social fraternity. He was elected to associate membership in The American Association of Petroleum Geologists in March, 1930.

It was the writer's privilege to be one of Allan's many close friends, attending the University with him the first two years of his four-year course. He was a large, rugged man and always enjoyed the best of health. All who were associated with him in his chosen profession were impressed by his diligence and persistence in the solving of any problem. His earlier work as an instrument man was so accurate as to cast the suspicion of "fudging notes" on him—a suspicion that was quickly dispelled. He was known among his associates as a well trained geologist of excellent character, good habits, and exceptional ability. Allan was unusually genial and understanding and was well liked by all with whom he came in contact. He leaves a host of friends.

ALLEN W. TILLOTSON

TULSA, OKLAHOMA
July 20, 1933

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 17, NO. 9 (SEPTEMBER, 1933), PP. 1157-1160

AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

EMPLOYMENT

The Association maintains an employment service at headquarters under the supervision of the business manager.

This service is available to members and associates who desire new positions and to companies and those who desire Association members and associates as employees. All requests and information are handled judiciously and gratuitously.

To make this service of maximum value, all members and associates in the Association are requested to coöperate by notifying the business manager of openings available.

NEWS

This department of personal news is of great use and interest to all members who read the *Bulletin*. Many have expressed their appreciation of it, but relatively few contribute to it,—possibly because of modesty. In order to avoid possible errors of printing items obtained from second-hand sources, it is hoped that members will keep headquarters informed of their own changes of address or occupation and professional activities of the kind which they like to read about other members. Send in your own items.

BOOKS

The Association occasionally has requests from members to find purchasers for their geological libraries. Because it is impracticable to print lists of such books in the *Bulletin*, it is suggested that persons desiring to purchase standard geological works or back numbers of geological journals at reduced prices write to Association headquarters, Box 1852, Tulsa, Oklahoma, so that they may be furnished with names and addresses of members who may have such books available.

William B. Sprague, geologist with The Texas Company, has been transferred from Houston to San Antonio, Texas.

C. W. Flagler, who has been in the geological laboratory of the Venezuela Gulf Oil Company, at Maracaibo, since 1928, has been transferred to Colombia, where his work includes subsurface correlation and general stratigraphy. His address is Cucuta, Colombia, in care of The Colombian Petroleum Company.

Roswell H. Johnson, professor of oil and gas production at the University of Pittsburgh, has been given a leave of absence for one year. The first half year will be devoted to study at Pittsburgh.

C. G. Carlson, consulting geologist, 703 National Bank of Commerce Building, Tulsa, Oklahoma, has an article in the July issue of *World Petroleum* entitled "Important Michigan Production."

George R. Elliott has opened an office as consulting petroleum engineer and geologist at Black Diamond, Alberta, Canada, and may be addressed at the Black Diamond Hotel Building.

P. L. Dana, formerly of 725 South Chestnut Street, Kewanee, Illinois, is now with the Gypsy Oil Company, Tulsa, Oklahoma.

D. A. McGee and William Norval Ballard have been transferred from the geological department of the Phillips Petroleum Company, at Oklahoma City, to the same company at Bartlesville.

E. B. Baldwin, formerly of Bellville, Texas, is district geologist for the Arkansas Fuel Oil Company, Houston, Texas. His address is 1802 Esperson Building.

Ruthven W. Pike has changed his address from 120 Broadway, New York City, to Standard Oil Company S. A. Argentine, General Ballivian FCCNA, Provincia de Salta, Argentina, S. A.

G. R. Henson, geologist for the Shell Petroleum Corporation, has been transferred from St. Louis, Missouri, to Houston, Texas.

W. P. Jenny, consulting geologist and geophysicist, has moved his office from Dallas to 2102 Bissonett, Houston, Texas.

Joseph M. Dawson, district geologist and agent for the Gulf Production Company in the San Antonio district, and Miss Virginia Beth Hendrix, of San Antonio, were united in marriage on June 20, 1933. The couple spent their honeymoon in Mexico City.

At the July 10 monthly meeting of the San Antonio Geological Society, M. C. Israelsky of the United Gas System and F. W. Rolshausen of the Humble Oil and Refining Company, both of Houston, Texas, presented notes on the paleontology of four deep wells in southwest Texas.

New officers of the Society of Economic Geologists for 1934–1935 are: president, W. E. Wrather, Dallas, Texas; first vice-president, Per Geijer, Stockholm, Sweden; secretary, D. H. McLaughlin, Cambridge, Massachusetts; councillors, F. W. DeWolf, Urbana, Illinois, B. L. Miller, Bethlehem, Pennsylvania, D. H. Newland, Albany, New York; regional vice-presidents, Hans Schneiderhohn, Freiberg, Germany, Eugene Stebinger, Buenos Aires, Argentina.

F. J. Miller, formerly of Hattiesburg, Mississippi, is now with the Arkansas Fuel Oil Company, 1802 Esperson Building, P. O. Box 283, Houston, Texas.

H. H. HENDERSON, petroleum geologist, has moved his office from 1022 Milam Building, San Antonio, to 1816 Second National Bank Building, Houston, Texas.

The Appalachian Geological Society held its regular monthly meeting on July 8, at the Bellefonte Country Club, Ashland, Kentucky. In addition to the business meeting, a golf tournament and banquet were enjoyed by members and their guests from Lexington, Ashland, and Charleston.

MAURICE R. TEIS is employed by the Phillips Petroleum Company of Bartlesville, Oklahoma.

C. MAYNARD BOOS is with the Phillips Petroleum Company with headquarters at Bartlesville, Oklahoma.

E. DEGOLYER has been appointed a special technical advisor to deputy administrator Simpson in the National Recovery Administration.

H. D. WILDE, JR., of the Humble Oil and Refining Company, Houston, Texas, has been made manager of technical research and development work in the refinery and production divisions of the company.

W. I. INGHAM has moved from Denver to 921 Nineteenth Street, Golden, Colorado.

VICTOR P. GRAGE has resumed work with the Gulf Refining Company of Louisiana after a year's absence during which time he was engaged in postgraduate work at the University of Oklahoma. His present address is Box 1731, Shreveport, Louisiana.

W. HAFNER, formerly of Hannover, Germany, is at Houston, Texas, with the Shell Petroleum Corporation.

GEORGE DICKINSON has moved from Birmingham, England, to Maracaibo, Venezuela, care of the Caribbean Petroleum Company.

JOSEPH L. ADLER, of the Michigan College of Mining and Technology, spoke before the Houston Geological Society, August 3, on "Lake Superior Iron Ore Deposits."

WALTER A. ENGLISH, geologist for the Superior Oil Company, Los Angeles, California, has been appointed a technical advisor to Hugh S. Johnson of the National Recovery Administration.

CLYDE M. BECKER, of Chickasha, Oklahoma, has leased mining claims at Vanadium, New Mexico, for development by eastern capital.

F. JULIUS FOHS, consulting oil geologist, has moved his office to 183 Madison Avenue, New York City. The Fohs Oil Company has its office in the Esperson Building, Houston, Texas.

R. M. OVERBECK has returned to the United States after several years in Europe. He is at 3 St. Johns Road, Roland Park, Maryland.

GEORGE OTIS SMITH has resigned as chairman of the Federal Power Commission at Washington, D. C.

The fourteenth annual meeting of the American Petroleum Institute will be held at Chicago, Illinois, October 24, 25, and 26.

H. C. GEORGE has resigned as director of the School of Petroleum Engineering at the University of Oklahoma to take a similar position at the University of Pittsburgh, Pennsylvania.

VERNON C. SCOTT, geologist for The Texas Company, has been transferred from the Colorado division to the Oklahoma-Kansas division. His address is Box 127, Perry, Oklahoma.

R. M. DANNENBERG, formerly of the Comar Oil Company, Marland, Oklahoma, is now production engineer for the Shell Petroleum Corporation, with headquarters at St. Louis, Missouri.

WALTER S. OLSON has changed his address from Baguio, Benguet, P. I., to Route 1, Box 317-A, San Diego, California.

A. MACLAY GARDNER is employed with the Oilfields Service Company of Long Beach and Los Angeles, California. This service includes locating the points of entry of underground water in oil wells.

WILLIAM V. HOYT, formerly of 440 Argo Avenue, San Antonio, Texas, may now be addressed at 1851 Columbia Street, Houston, Texas.

A. J. CHILDERHOSE, geologist for The Texas Company, has been transferred from Cut Bank, Montana, to Beeville, Texas. His address is Box 787.

At the August 7 monthly meeting of the San Antonio Geological Society the program consisted of a round table discussion: "Factors Controlling the Accumulation of Oil in the Laredo District," led by Herschel H. Cooper and Charles H. Row. Nearly 100 southwest Texas geologists attended.

BURR MCWHIRT, who has been taking special postgraduate petroleum courses during the past three years, has recently received the degrees of Bachelor of Science in geology and Bachelor of Science in petroleum engineering. McWhirt was formerly valuation engineer for the Shell Petroleum Corporation.

G. H. WESTBY has resigned from the geological department of the Empire Oil and Refining Company at Bartlesville to accept affiliation with the Seismograph Service Corporation, Kennedy Building, Tulsa, Oklahoma, as a director and vice-president. His efforts will be devoted mainly to seismic interpretation.

JOSEPH PURZER of Tulsa has accepted a position in the geological department of the Phillips Petroleum Company at Bartlesville.

JOHN S. CRUSE, JR., paleontologist, formerly with the Pure Oil Company, has joined the Amerada Petroleum Corporation at Houston, Texas.

JOHN F. KINKEL is now in the geological department of the Phillips Petroleum Company at Bartlesville, Oklahoma.

VIRGIL O. WOOD, consulting geologist of the firm of Wood and Wood, Beacon Life Building, Tulsa, Oklahoma, has been in Santa Monica, California, the past summer.